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Concentrating Whey by Hyperfiltration at a Small Canadian Cheese Plant

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CONCENTRATING WHEY BY HYPERFILTRATION AT A SMALL CANADIAN CHEESE PLANT

by

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on behalf of

La Fromagerie d'Oka
Oka, Quebec

and the

Environmental Protection Programs Directorate
Environmental Protection Service
Environment Canada

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ABSTRACT

Whey from cheese making operations, if simply discharged to the aquatic environment, exerts an extremely high pollution load. While large cheese making plants have been able to incorporate various recovery, reuse, and treatment schemes, no cost-effective method of handling whey has been available to smaller operations. This report describes the application of a hyperfiltration system for concentrating the solids in sweet whey at La Fromagerie d'Oka, Oka, Quebec, a cheese making plant with a production of 4 256 kg/d. Hyperfiltration offered the potential for recovery of a whey concentrate which could be used in the manufacture of edible products, while also reducing the pollution load from the cheese plant. The results of a 592-day evaluation of the system showed that whey could be concentrated from an initial 6.24% solids to 24.1% solids, with a high recovery of protein and minerals. At the same time, major pollutant parameters in the raw whey were reduced by more than 95%. The payback period for the hyperfiltration system was calculated at 14 months when savings in wastewater treatment are considered and the concentrated whey is given away free of charge. If the whey were to be sold, the payback period would decrease proportionally with the amount of revenue recovered. The study recommends that hyperfiltration for whey concentration be considered in any economic evaluation of pollution abatement/by-product recovery schemes for cheese making plants of similar size, taking into account the site-specific characteristics of the operation.

RÉSUMÉ

S'il est simplement rejeté dans le milieu aquatique, le lactosérum de fromagerie est très polluant. Les grosses fromageries ont réussi à le récupérer, à le traiter et à le réutiliser de diverses façons, mais les petites ne pouvaient pas compter sur une méthode rentable de traitement. Le présent rapport décrit un dispositif d'hyperfiltration permettant de concentrer le lactosérum doux à la Fromagerie d'Oka, au Québec, qui produit 4 256 kg/j de fromage. L'hyperfiltration offrait la possibilité de récupérer un concentré de lactosérum transformable en produits comestibles tout en réduisant la pollution créée par la fromagerie. Après 592 jours d'évaluation, le dispositif s'est révélé capable de concentrer le sérum, d'un taux initial de matières solides de 6,24%, à un taux de 24,1% tout en récupérant beaucoup des protéines et des minéraux et en réduisant de plus de 95% la concentration des principaux polluants. D'après les calculs, le dispositif se rentabilise en 14 mois, si on tient compte des économies au poste du traitement des eaux usées et si on se débarrasse du concentré en le donnant. Si le concentré était vendu, le délai de rentabilité se réduirait en proportion du produit de la vente. Il est recommandé d'envisager l'hyperfiltration lors de l'évaluation économique de tout plan de réduction de la pollution et de récupération des sous-produits destiné à des fromageries de grandeur similaire, compte tenu aussi de leurs caractéristiques propres.

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CONCLUSIONS AND RECOMMENDATIONS

1) Hyperfiltration as a solids concentration technology for sweet whey should be considered in any economic evaluation of pollution abatement/by-product recovery schemes for cheese producers. This applies specifically to those cheese producers who are considering a change in their current whey handling procedure.
2) Depending on local circumstances concerning whey discharge, whey concentration and recovery can result in significant economies to a cheese manufacturer.
3) If the whey concentrate is given away free of charge, calculations for the use of hyperfiltration indicate that La Fromagerie d'Oka could save as much as 108 cents per kg of solids compared with waste treatment.
4) A payback period of 14 months has been calculated when considering concentration of whey only and giving it away free of charge.
5) If the cheese manufacturer can either sell the concentrated whey or use it as a feed-stock for the manufacture of other edible products, further significant cost savings beyond those indicated can be realized.
6) The site specific characteristics of any cheese manufacturing operation, as well as the many variables involved in whey recovery, whey treatment and/or disposal of process effluents, do not permit one to make specific cost statements. Each cheese manufacturing operation must be evaluated on its own merits.
7) The application of hyperfiltration technology for sweet whey from cheese producers is a solids concentration technology which can be used without great difficulty by even the small cheese producer.
8) In all cases a feasibility study is an essential prerequisite to the identification of the most cost-effective management strategy for the sweet whey problem.
9) Future hyperfiltration systems should be operated on a closed loop principle because considerably less energy would be required, and the whey would be less susceptible to bacterial contamination.
10) A market for concentrated whey must be developed through the manufacture of edible products either for human consumption or for animal feed.
11) For the effective operation of a hyperfiltration system the following points should receive serious consideration:
    - A good start-up liaison between supplier and user is necessary.
    - A spare parts inventory is required.

- The operator must be shown how the equipment is set-up as well as dismantled.
- The operator should have an operations chart to monitor process performance.
- The operator selected to run the system must have a mechanical aptitude.
- Care must be taken to ensure that the membranes are always moist.
- Oil levels in booster pump gear boxes must be checked daily.
- Gear boxes must receive adequate lubrication.
- If one set of seals on one booster pump fails, the seals in all other pumps should be replaced too.
- The permeate flow meter must be calibrated periodically.
- The danger of membrane blow-out increases when the system is operated at pressures >4200 kPa.
- A minimum of 120 minutes should be allowed for circulation of disinfectant during system cleaning.

1 INTRODUCTION

While whey from cheese making operations is recognized as a potentially valuable by-product, the economy of scale of the cheese-making operation generally dictates the end use of the whey. Whey, if simply discharged as a waste to the environment exerts an extremely high pollution load. Solutions used by large operations in addressing this problem have ranged from complete recovery of whey through evaporative processes for feed stock for new dairy products, to treatment within the plant or by the municipality, to use as animal feed.

No cost-effective method of handling the whey problem has existed for smaller cheese plant operations. La Fromagerie d'Oka Inc. of Oka, Quebec is a cheese-making operation where alternatives to whey discharge to the environment had to be explored. Table 1 indicates the distribution of cheese plant sizes in Canada. With a mean cheese production of 4 256 kg per day, Fromagerie D'Oka is typical of the more than 50% of Canadian cheese producing plants.

TABLE 1 CAPACITY DISTRIBUTION OF CHEESE PRODUCING PLANTS IN CANADA

Capacity (kg/d)	Number of Plants
<11 000	90
11 001 - 24 000	28
24 001 - 45 000	38
45 001 - 91 000	14
91 001 - 227 000	7
>227 000	5

A small cheese-manufacturing plant was originally established in Oka by Trappist monks in 1882. The manufacturing process was primitive and very labour intensive. Because of a continuing decrease in the number of monks and more stringent provincial and federal plant and sanitary standards, the Trappists decided to divest themselves of the cheese-making operation in 1975. After its sale to new owners an extensive modernization program was initiated. This included the construction of

additional floor space, installation of the most modern cheese-making equipment, and renovations to the existing cheese aging cellars at a cost of $1.8 million dollars (1977-1979).

La Fromagerie d'Oka had disposed of its whey into the lake of Two Mountains until early 1977. This discharge and the increased plant capacity imposed an intolerable pollution load on the lake. La Fromagerie d'Oka investigated a variety of alternatives in seeking an acceptable method of handling the whey, i.e.:

1) ship the raw whey to an evaporating plant in Montreal,
2) dump whey on a large land area nearby,
3) install a vacuum evaporation system, or
4) install a membrane filtration process.

High transportation costs, limited year-round access to land, high capital costs, etc. all contributed to the elimination of alternatives 1 to 3.

Installation of a membrane filtration process became financially more attractive when it became apparent that a grant might be available from the federal government to underwrite a portion of the project cost. This would be in addition to the benefit of recovering concentrated whey for potential use in the manufacture of secondary products.

Under the federal government's Demonstration of Pollution Abatement Technology (DPAT) program, a cost-shared program with La Fromagerie d'Oka was initiated in early 1978. The concept was that a technology for pollution abatement through by-product recovery would be assessed in an operating environment with respect to cost, operation, degree of pollution reduction, by-product recovery and reliability of operation. Based on the results of the study program the feasibility of applying this technology for cheese manufacturing operations similar to La Fromagerie d'Oka could then be assessed.

Equipment aquisition, laboratory construction and site preparation took place during 1978. Installation of the hyperfiltration equipment began in January 1979. The demonstration phase started in June 1979 and concluded in March 1981. The total of some 500 operational days' observations provided considerable insight into the applicability of this technology for the small cheese producer.

2 THE WHEY PROBLEM

2.1 Production of Cheese Whey

Whey is the residue after fat and casein have been removed from milk in the cheese-making process. The characteristics of whey and its value as a feed stock for animal feed and/or edible products has been reported extensively in the literature (1). There are two types of whey, acid whey (pH 4-5) from cottage cheese making operations, and sweet whey (pH 5-7) resulting from cheddar and specialty cheese making. This study concerns the hyperfiltration of sweet whey from a specialty cheese. Conventionally, three sizes of cheese-making operations have been defined, as shown in Table 2.

TABLE 2 SIZE DEFINITIONS FOR CHEESE MAKING PLANTS (2)

Plant Size	Quantity of Milk Received (kg/day)	Quantity of Whey Produced (kg/day)
small	9 100	7 700
medium	45 500	38 600
large	91 000	77 300

The quantity of milk received and processed into cheese at La Fromagerie d'Oka is 39 236 kg/d 50% of the time. According to Table 2 this puts La Fromagerie d'Oka into the upper end of the small plant category.

The literature reports that for every kg of cheddar cheese produced, 9.5 kg of raw milk is required and 8.5 kg of sweet whey results (1). The data for this study show corresponding values of 9.22 kg raw milk resulting in 8.36 kg whey per kg of cheese produced.

The total amount of whey produced per year at La Fromagerie d'Oka averages 8 926 200 kg (250 working days). It is this quantity of whey that must be handled either through utilization, disposal or a combination of the two.

Analysis of the plant data (Table 3) provided showed that 50% of the time 39 236 kg per day of milk were received at the cheese plant (Figure 1). The data indicated normal distribution with a coefficient of variation of 13.5. Data for cheese production showed a 50% value of 4 256 kg per day and coefficient of variation equalling

TABLE 3 PRODUCTION DATA FOR FROMAGERIE D'OKA

Day	Date	Milk (kg)	Raw Whey Quan (kg)	Raw Whey Conc (%)	Permeate Quan (kg)	Permeate Conc (%)	Concentrate Quan (kg)	Concentrate Conc (%)	Cheese (kg)	Raw Whey Mass/ Milk Mass	Raw Whey Mass/ Cheese Mass	Permeate Mass/ Conc Mass	Conc Solids Raw Whey Solids	Raw Whey Mass/ Conc Mass	Permeate Mass/ Raw Whey Mass	Permeate Mass/ Milk Mass
1	190579	36377	32490	5.2	23924	0.09	8566	39.6	3887	0.89	8.36	2.79	7.52	3.79	0.74	0.66
10	280679	37421	33443	6.0	25913	0.27	7529	40.6	3887	0.89	8.60	3.44		4.44	0.77	0.69
17	50779	37421	33443	6.1	26178	0.12	7264	38.7	3977	0.89	8.41	3.60	6.02	4.60	0.78	0.70
24	120779	37421	33443	6.3	25536	0.15	7905	10.7	3977	0.89	8.41	3.23	1.70	4.23	0.76	0.68
120	161079	47626	44315	5.3	30007	0.44	14308	37.6	4762	0.93	9.31	2.10	5.97	3.10	0.68	0.63
127	231079	47626	43272	5.2	29074	0.18	14198	34.5	4758	0.91	9.09	2.05	5.56	3.05	0.67	0.61
134	301079	47626	40097	5.4	27929	0.29	12157	41.7	4762	0.84	8.42	2.30	6.52	3.30	0.70	0.59
141	61179	47626	43838	5.3	33117	0.30	10534	41.0	4762	0.92	9.17	3.14	6.51	4.14	0.75	0.70
288	10480	36796	15504	5.3	10197	0.15	5355	22.0	3862	0.42	4.03	1.90	3.49	2.90	0.65	0.28
295	80480	35792	14785	5.7	10894	0.22	3892	27.0	3548	0.44	4.17	2.80	4.03	3.80	0.74	0.32
301	140480	27033	23345	5.1	14699	0.20	8545	23.5	2855	0.86	8.18	1.70	4.51	2.70	0.63	0.54
309	220480	37171	33454	5.3	23316	0.15	10137	22.0	3914	0.90	8.54	2.30	3.49	3.30	0.70	0.63
316	290480	29755	25779	5.3	17542	0.22	7237	29.0	3137	0.90	8.62	2.70	4.60	3.70	0.73	0.66
322	50580	30413	27367	5.2	20118	0.20	7735	26.0	3178	0.92	8.77	2.60	4.19	3.60	0.72	0.66
329	120580	27510	25439	5.2	18171	0.12	7268	24.0	3271	0.92	7.78	2.50	3.87	3.50	0.71	0.65
336	190580	0	0	5.3	0	0.13	0	24.0	0				3.81			
343	260580	33792	31405	6.0	21613	0.14	10292	22.0	3514	0.94	9.08	2.10	3.57	3.10	0.68	0.64
351	30680	38532	35796	6.0	24249	0.13	11547	33.0	4063	0.93	8.81	2.10	5.50	3.10	0.68	0.63
358	100680	41254	35796	5.9	24610	0.11	11186	17.0	4365	0.87	8.20	2.20	3.22	3.20	0.69	0.60
365	170680	41911	38574	6.5	26124	0.15	10449	24.0	4434	0.87	8.25	2.50	3.59	3.50	0.71	0.62
379	10780	35243	31719	5.1	21487	0.14	10232	25.0	3740	0.90	8.48	2.10	4.59	3.10	0.68	0.61
386	80780	41856	37579	5.4	26201	0.15	11415	21.0	4396	0.90	8.57	2.30	3.28	3.30	0.70	0.63
392	140780	41480	37332	6.9	23999	0.19	13333	24.0	4395	0.90	8.40	1.80	3.48	2.80	0.64	0.58
399	210780	43272	38945	5.0	25036	0.17	13903	0.0	4544	0.90	8.57	1.80	0.00	2.80	0.64	0.58
428	190880	43230	38952	5.9	25040	0.19	13911	19.9	4799	0.90	8.12	1.80	3.37	2.80	0.64	0.58
448	80980	39123	38902	6.2	27792	0.27	11117	32.0	4720	0.99	8.24	2.50	5.16	3.50	0.71	0.71
455	150980	41911	40405	6.5	25805	0.20	15860	19.0	5190	0.97	7.80	1.40	4.22	2.40	0.59	0.56
462	220980	44113	42877	6.7	27504	0.25	15313	21.0	4834	0.97	8.87	1.60	3.13	2.60	0.64	0.62
469	290980	37658	33893	6.5	22887	0.15	10955	30.0	4159	0.90	8.15	2.03	4.62	3.10	0.67	0.60
476	61080	38478	35571	5.0	23502	0.13	12359	28.0	4359	0.93	8.23	1.90	4.67	2.90	0.66	0.61
483	131080	41712	38496	5.9	23401	0.14	15034	24.0	4808	0.87	7.59	1.80	4.07	2.80	0.64	0.56
490	201080	43408	39306	6.2	30165	0.14	9141	21.0	5016	0.91	7.84	3.30	3.34	4.30	0.77	0.69
497	271080	43374	40035	5.1	28624	0.14	14011	24.0	5328	0.94	7.63	1.90	3.93	2.90	0.65	0.61
511	101180	44427	40202	5.7	26334	0.14	13853	20.0	4704	0.90	8.55	1.90	2.99	2.90	0.65	0.59
518	171180	44020	39431	6.3	24826	0.19	14504	20.0	5001	0.90	7.88	1.70	3.17	2.70	0.63	0.56
525	241180	40445	35225	5.1	25441	0.17	9785	27.0	4747	0.87	7.42	2.60	4.43	3.60	0.72	0.63
539	81280	35359	32038	5.4	22026	0.12	10312	26.0	3937	0.91	8.14	2.20	4.06	3.20	0.69	0.62
545	151280	35486	31067	6.1	20711	0.13	10355	27.0	3927	0.88	7.91	2.00	4.43	3.00	0.67	0.58

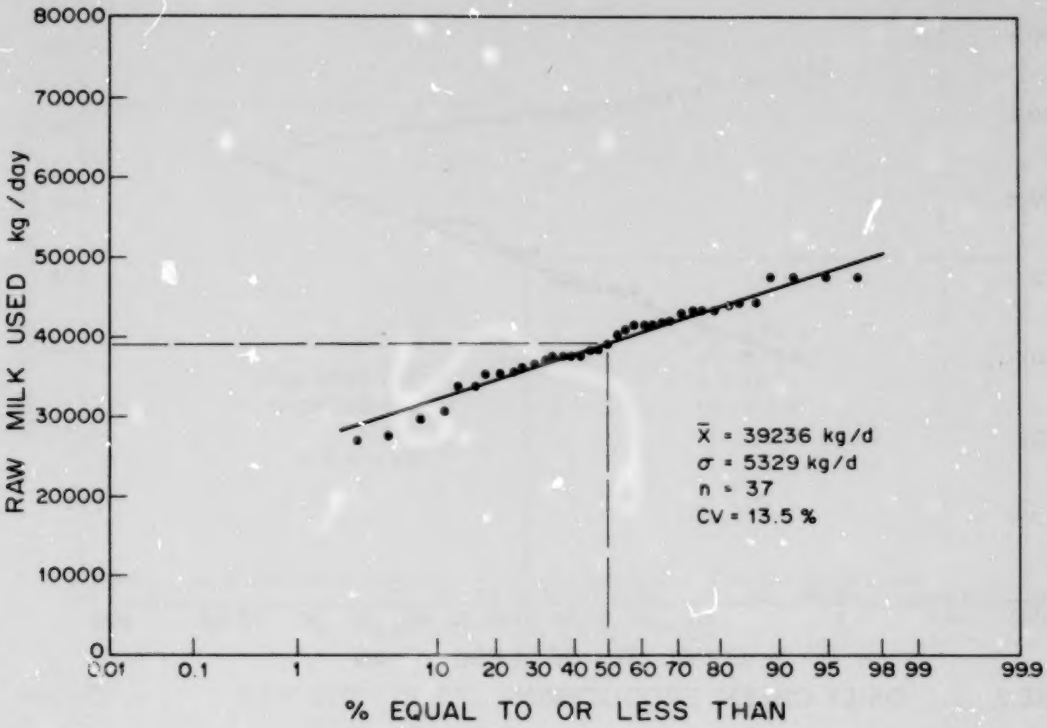


FIGURE 1 RAW MILK USED FOR CHEESE PRODUCTION AT FROMAGERIE D'OKA

14.3 (Figure 2). Since raw milk and cheese quantity data are closely tied to the economies of a cheese manufacturing operation, considerable care is taken to record these values. On the other hand, this is not necessarily true for the resulting whey quantities during cheese production.

Surprisingly, the raw whey/milk ratio data showed that the raw whey data collected was consistent with a mean value of 0.91 and a coefficient of variation of 3.4 (Figure 3).

Further statistics concerning the raw whey solids concentration were analyzed after the deletion of three values judged to be atypical. The mean raw whey solids concentration for the remaining 49 pieces of data was determined to be 6.24%. The coefficient of variation was calculated to be 3.4. As shown in Figure 4, the data are normally distributed.

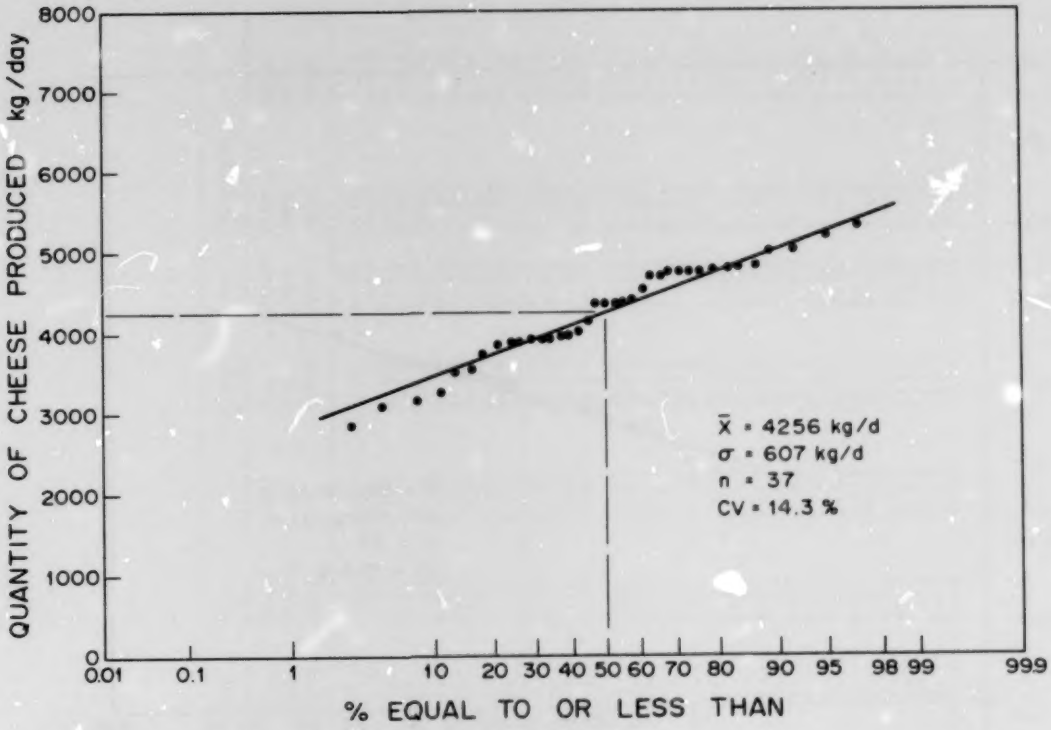


FIGURE 2 DAILY CHEESE PRODUCTION

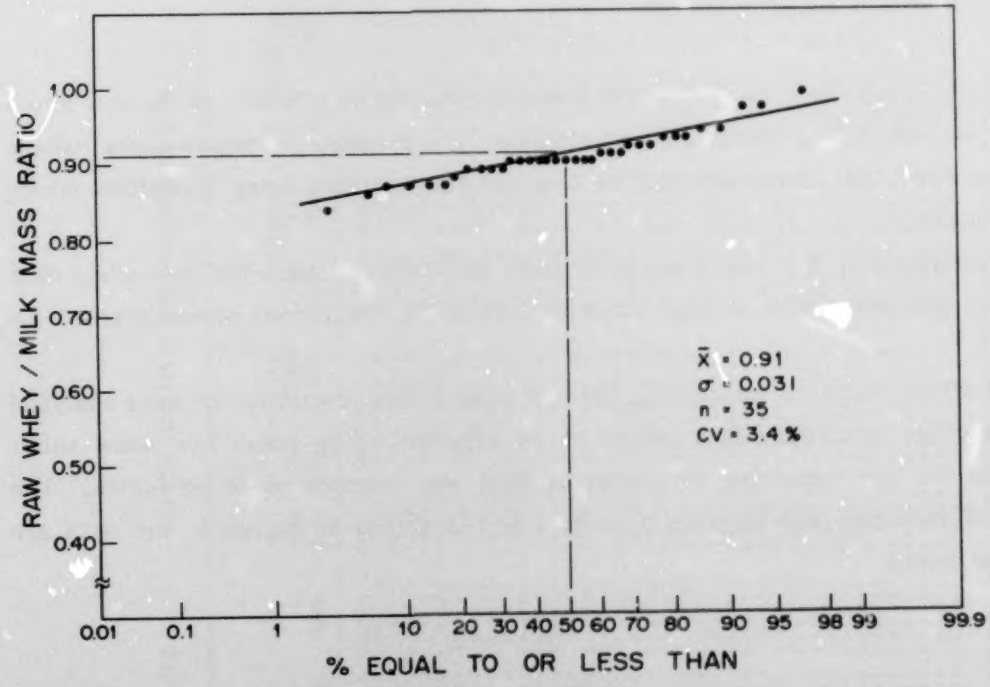


FIGURE 3 RAW WHEY TO MILK RATIO

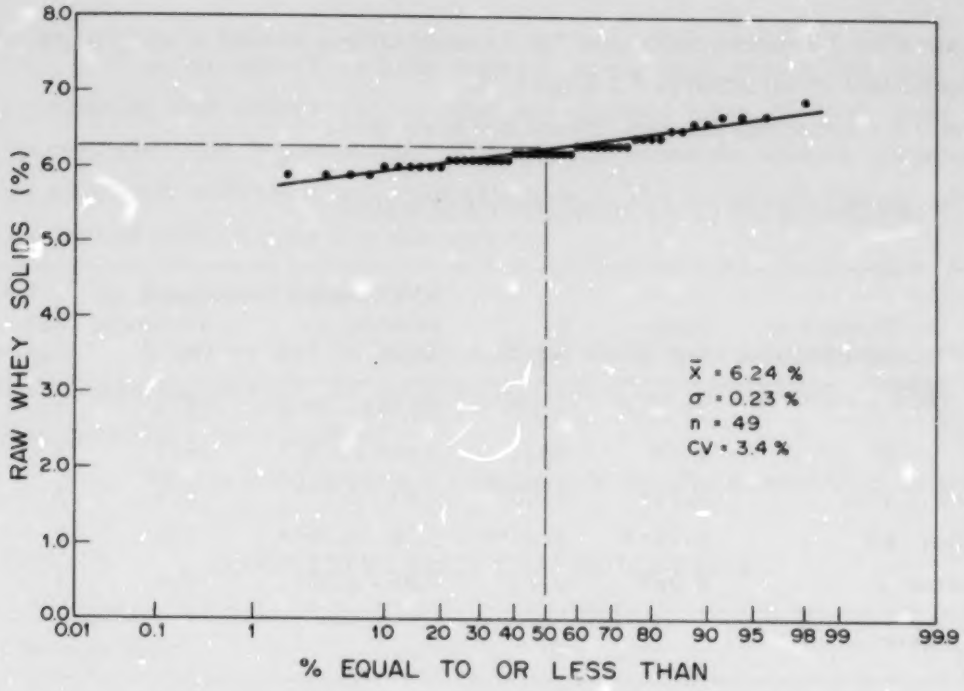


FIGURE 4 RAW WHEY TOTAL SOLIDS

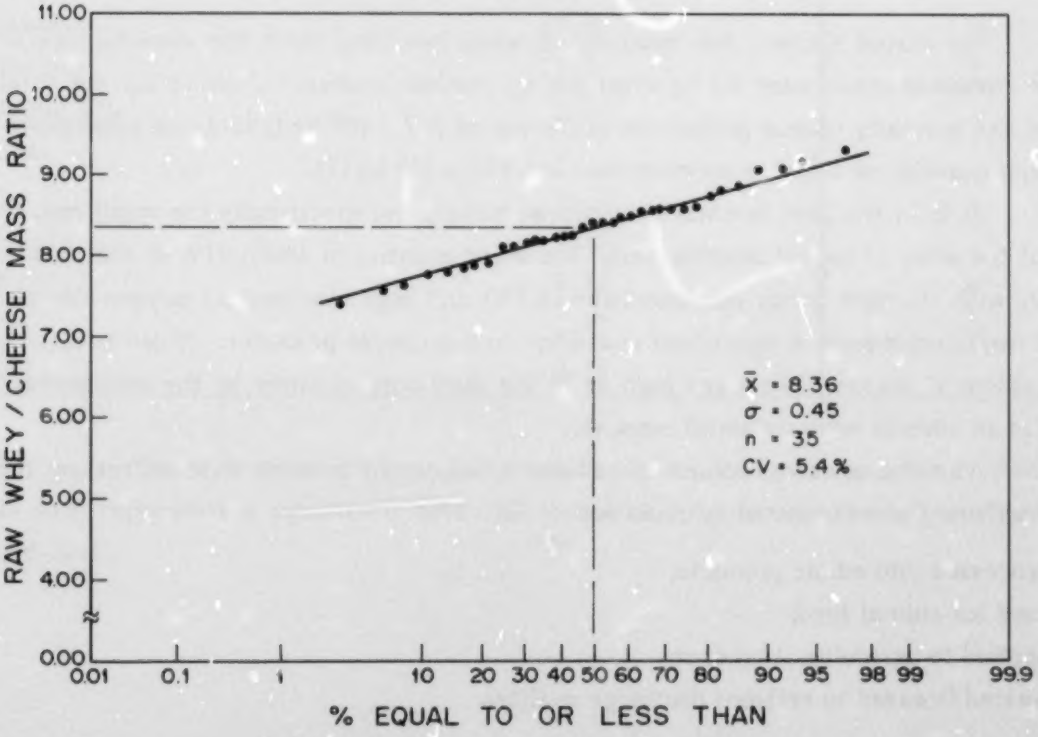


FIGURE 5 RAW WHEY TO CHEESE PRODUCED RATIO

Raw whey to cheese ratio data for 35 observations showed a mean value of 8.36 with a coefficient of variation of 5.4 (Figure 5).

Table 4 summarizes the milk, cheese and whey data.

TABLE 4 PRODUCTION CHARACTERISTICS SUMMARY

Parameter	Number of Observations	Mean (kg/d)	σ (kg/d)	95% Confid. Interval (kg/d)	Coeff. of Variation (%)	Ref. Figure
Milk	37	39 236	5 329	28 578 - 49 894	13.5	1
Cheese	37	4 256	607	3 649 - 4 863	14.3	2
Raw whey/milk	35	0.91*	0.03*	0.85 - 0.97*	3.4	3
Raw whey solids	49	6.24**	0.23**	5.78 - 6.70**	3.4	4
Raw whey/cheese	35	8.36*	0.45*	7.46 - 9.26*	5.4	5

* dimensionless
** percent

2.2 Whey Handling and Disposal

As stated earlier, the quantity of whey resulting from the manufacture of cheddar cheese approximates 9.5 kg whey per kg cheddar cheese. Considering the total cheddar and specialty cheese production in Canada of 177 x 10^6 kg (1981), the corresponding annual quantity of sweet whey generated is 1 690 x 10^6 kg (3).

It is in the best interest of a cheese maker, and specifically the small one, to be rid of the whey at lowest possible cost. The sheer quantity of whey, 91% of the volume of milk, with its high solids concentration (6.2%) and high biochemical oxygen demand (30 000 mg/L) represents a significant challenge to the cheese producer. It can become a real problem if disposal costs are high or if the discharge of whey to the environment results in an adverse environmental response.

The cheese manufacturer does have a number of options when addressing the whey problem. For example whey could be:

1) processed into edible products,
2) used for animal feed,
3) applied to agricultural land, or
4) wasted (treated to effluent discharge quality).

In an age of variable interest rates, high energy and high labour costs, technologies that reduce the handling and disposal costs of whey must be explored, demonstrated and implemented. The current economic climate dictates that whey recovery and utilization are cost-effective. The challenge lies in identifying the appropriate solution since it is site-specific.

2.3 By-product Recovery

Recovery and utilization of by-products from industrial processing activities rather than disposal are the technological strategies of the 1980s. Whey from cheese manufacturing is no exception.

Typical dried sweet whey concentrate has characteristics as shown in Table 5.

TABLE 5 DRIED SWEET WHEY CHARACTERISTICS

Characteristic	%	Reference
moisture	4.5	5
fat	1.1	
protein	12.9	
lactose	71.2	
lactic acid	2.3	
ash	8	
Ca	0.72	6
P	0.52	
K	2.88	
Na	1.13	
Mg	0.12	

Sweet whey is rich in protein, lactose, amino acids, vitamins and minerals, and as such represents a significant potential source of feed stock suitable for a variety of end-uses.

Countries around the globe that volunteered whey processing and utilization information in a 1972 survey present an interesting picture as summarized in Table 6. The information shows diverse whey disposal practices, ranging from 0% wasted in Denmark to 84% wasted in Israel. Sweden reported that it is illegal to discharge whey to a sewerage system. The range in quantities of whey used for animal feed is equally large; 0% in Israel to 90% in Denmark. All of the countries surveyed, except the province of Victoria in Australia, reported some degree of whey processing into useful by-products. The Netherlands lead the way with 93% of its whey being processed.

The Canadian data base indicates 44% of the whey produced is wasted, 8% fed to animals, and 48% processed (4). A more recent report prepared by Inmarit Company for Agriculture Canada entitled, "Economic Evaluation of Liquid Whey Feeding to Livestock", indicates that whey feeding in Canada is on the increase. Still, there are several hundred million kilograms of whey being wasted.

By-product recovery for proteins and lactose specifically is accomplished using concentration technologies ranging from spray drying to ultrafiltration coupled with gel filtration. The choice of technology is a function of end product use criteria.

Food uses for whey have encompassed pharmaceutical products, dairy products, bakery products, confections and coatings, frozen and canned foods as well as powdered foods. The production of whey powder in Canada has increased from 41×10^6 kg in 1977 to 57×10^6 kg in 1981.

The 1690×10^6 kg of sweet whey generated in Canada annually represent significant source of protein, lactose and minerals. The quantities for a 6% solids concentration approximate:

15×10^6 kg protein
57×10^6 kg lactose
6×10^6 kg minerals

The economic disbenefit of not using this material is compounded when the significant adverse impact on the environment if the whey is merely wasted is considered. The cost of pollution control is considerable. It is therefore imperative to capitalize on by-product recovery and whey utilization opportunities.

TABLE 6 SUMMARY OF WHEY PROCESSING AND UTILIZATION SURVEY, 1972 (4)

Country	Whey Produced (x 10^6 kg)	Disposition (%)			Ex-Factory Price for Further Processing (cents/cwt)
		Processed	Animals	Wasted	
Victoria (Australia)	600 (1 459)	0	42	58	Nil
Belgium	249	75	15	10	10-12
Bulgaria	273	17	74	9	25
CANADA[a]	**1 183**	**48**	**8**	**44**	**unknown**
Switzerland	996	7	rest	very small	29-43[c]
Germany	630(?)	67	?	?	"nearly nil"
Denmark	1 084	10	90	0	23-30[c]
Spain	300	50	17	33	4-45
Israel	189	16	0	84	No trade
Japan	100	?	?	10	Unclear
Netherlands	2 662	93	7	0	45
New Zealand	1 830	25	30	45	0 - small
Poland	1 373	4	84	12	0.9 - 3%[d]
Sweden	558	66	34	Illegal	9 - 18
Finland	392	60	40	0	10 - 40
USSR	>3 500	5 - 30	70	0 - 20	9
South Africa	161	22	56	22	No sale
(U.K.[b])	(1 432)	Most	37	?	

a 1981 data, 1 690 x 10^6 kg whey produced

b Not in survey

c As animal feed

d 0.9% of milk price for animal feeding; 2.4-3.0% of milk price for processing

2.4 Pollution Control Aspects

A proper strategy for industrial pollution control consists of minimizing feedstock leakage, optimizing product conversion efficiency, maximizing recovery and recycle of process losses, and optimizing by-product generation. All of these measures will reduce the volume and mass of substances which wind up as waste.

To accomplish these tasks it is imperative that a company conduct an in-house study. Such a study is designed to identify opportunities that will permit the application of any or all of the measures identified above. The objective as stated above is to reduce the amount of waste material which results from the particular industrial activity and thus minimize the company's economic burden in complying with pollution control requirements. For many industries, by-product generation results in an economic spin-off which more than pays for the cost of pollution control.

Sweet whey in its raw form represents a significant pollution potential. Table 7 summarizes some of the sweet whey characteristics in context with the standard pollution parameters: pH, biochemical oxygen demand (BOD), chemical oxygen demand (COD), total solids (TS), and ammonia nitrogen (NH_3-N).

TABLE 7 SUMMARY OF PERTINENT SWEET WHEY CHARACTERISTICS FOR LA FROMAGERIE D'OKA

		Characteristics				
Description	Units	pH	BOD_5	COD	TS	NH_3-N
mean, $\bar{x}$	mg/L	6.22	29 500	64 000	62 400	113
standard deviation, σ	mg/L	0.57	3 900	4 800	2 300	69
coefficient of variation, CV	%	9	13	7.5	3.4	61
number of observations, n	-	45	41	44	49	45
Reference (2)		5-7	30 000 - 50 000	-	67 000	-

Note - pH is unitless

The impact of raw whey on the aquatic environment is four-fold. It results in significant reductions in dissolved oxygen, has adverse effects on fish (lack of oxygen) and the fish respiratory system (irritation), and results in significant deposition of solids.

2.4.2 Standard pollution parameters

The biochemical oxygen demand (BOD) is used as a measure of waste strength. It defines the amount of oxygen that is required to stabilize an organic waste under non-nutrient limiting conditions. It must be recognized though that the BOD is measured over a five-day period (BOD_5) only, and thus represents approximately 68% of the ultimate BOD (BOD_u). In the long run a receiving body of water must satisfy the ultimate BOD.

In this study the median BOD_5 based on 41 observations was determined to be 29 500 mg/L. It can be stated with 95% confidence that:

$$BOD_5 = 29\,500 \pm 7\,800 \text{ mg/L}$$

Based on a mean daily sweet whey production of 35 700 kg, the mean daily BOD_5 on a mass basis is 1 050 kg. It can be calculated that the 95% confidence interval for the BOD_5 load is 500-1 600 kg/d. This represents a significant impact on the oxygen resources of a receiving water. The worst condition usually occurs during the summer when both the dissolved oxygen saturation level and flows are low. Once dissolved oxygen levels in receiving bodies of water drop below 4 mg/L, all but coarse fish are in distress.

Raw whey total solids concentrations (TS) in this study were determined to have a mean value of 62 400 mg/L (49 observations). The 95% confidence interval for the total solids is:

$$TS = 62\,400 \pm 4\,600 \text{ mg/L}$$

Similar to the BOD_5 mass calculation, it can be calculated that the mean daily TS mass load is 2 230 kg. The 95% confidence interval for the total solids load is 1 900-2 560 kg/d.

Discharge of solids to the environment not only causes severe visual pollution problems but results in deposits which, if biodegradable, will undergo anaerobic decomposition. For whey this is characterized by heavy black sludge and strong butyric acid odours caused by the decomposition of casein. It is readily apparent why the discharge of whey solids to the environment must be minimized.

Ammonia is another undesirable compound which, if discharged to receiving waters, will affect the well-being of the aquatic environment. Unionized ammonia even in low concentrations (<0.005 mg/L) can be acutely toxic to many species of fish. As well, ammonia in potable water supplies results in a larger requirement for chlorine and, therefore, the generation of chloramines.

The raw whey ammonia concentration in this study was determined to be 113 mg/L. The 95% confidence interval for the ammonia concentration was:

$$NH_3 - N = 113 \pm 138 \text{ mg/L}$$

On a mass basis this is 0-12 kg NH_3-N/d. As indicated in Table 8 the ammonia data are highly variable (coefficient of variation = 61%).

2.4.2 Effect of whey recovery on potential pollution load

The recovery of whey has a profound effect on strength of the final process effluent that is discharged from the cheese making operation. This is illustrated in Table 8.

TABLE 8 CHEESE WHEY EFFLUENT CHARACTERISTICS WITH AND WITHOUT WHEY RECOVERY

	Raw Whey		Whey Recovered Combined Effluent*		Whey **Not** Recovered Total Discharge	
Q	35.7 m^3/d		39.8 m^3/d		43 m^3/d	
Units	mg/L	kg/d	mg/L	kg/d	mg/L	kg/d
COD	64 000	2 280	1 700	68	54 600	2 350
BOD_5	29 500	1 050	880	35	25 400	1 090
TS	62 400	2 230	4 370	174	55 800	2 400
NH_3-N	113	4	-	negl.	-	-
pH**	6.2	-	-	-	-	-

* contains permeate + washwater
** unitless

Process washwater and permeate (combined effluent) are liquid streams which still require the application of a control strategy. The total organic and solid load is small. If whey is not recovered, then for all practical purposes the total effluent concentration is nearly identical to the raw whey concentration. Whey recovery reduces the potential COD and BOD_5 loads to the environment by 97%, and total solids loads by 92%. This is an excellent example of applying technology to achieve simultaneously a high degree of product recovery and pollution abatement.

Pollution loads are generally expressed in terms of population equivalents (p.e.). If one p.e. is defined as being equal to 77 g BOD_5/person•d, the pollution load from La Fromagerie d'Oka equals 450 persons if whey recovery is practiced and 14 200 if no whey recovery is practiced.

2.4.3 Pollution control technology

In the past pollution control technology for process effluents from the cheese making industry has followed three strategies:

a) direct discharge to the municipal system,
b) pre-treatment at the cheese plant followed by discharge to the municipal system, or
c) full treatment by the industry.

The biological treatment of whey is not without problems. Even though whey is nutrient-balanced, the lactose fraction causes the bacterial population to swing toward filamentous organisms which are unable to use the amino acids present as a nitrogen source. The protein molecules, because of their large size, are unable to pass through the bacterial cell wall. In time extracellular enzymes break down the large protein molecules, but only relatively small quantities of whey can be oxidized at a time.

In many cases a cheese plant is located in a rural area and, if a municipal waste treatment system exists, the cheese plant effluents will exert an overwhelming influence on the municipal plant. Invariably the organic load coming from the cheese plant will be many times greater than the organic load from the community. The organic loading rate to the treatment plant will not be constant unless load equalization is practised. The process reponse will be erratic unless extremely long system retention times are available. Experience has shown that the BOD_5 concentration to a biological system treating largely whey should not exceed 1 000 mg/L. At concentrations larger than this severe bulking problems have been experienced. As shown in Table 8, the BOD_5 is 880 mg/L. If the whey is not recovered, then the total effluent BOD_5 is estimated to be 25 400 mg/L.

In order to ensure that the combined influent from a cheese plant and a community does not exceed 1 000 mg/L BOD_5 the following mass balance calculation to determine minimum community size can be made:

Cheese Plant

Whey Not Recovered

Q_1 = 43.0 m^3/d

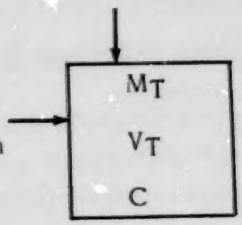
R_1 = 1 090 kg BOD_5/d

Community

Q_2 = 0.4 $m^3/d \cdot person$

R_2 = 0.077 kg $BOD_5/d \cdot person$

Ca = number of persons



Treatment Plant

C = 1 000 mg BOD_5/L = 1 g BOD_5/L = 1 kg BOD_5/m^3

$M_T = M_1 + M_2$ (1)

$V_T = V_1 + V_2$ (2)

$V_T = t(Q_1 + Q_2\,Ca)$

$M_1 = R_1 t$

$M_2 = R_2 t\,Ca$

$$\therefore \quad C = \frac{M_T}{V_T} = \frac{t(R_1 + R_2\,Ca)}{t(Q_1 + Q_2\,Ca)} = \frac{R_1 + R_2\,Ca}{Q_1 + Q_2\,Ca} \qquad (3)$$

$C(Q_1 + Q_2\,Ca) = R_1 + R_2\,Ca$

$CQ_1 + CQ_2Ca = R_1 + R_2\,Ca$

$$Ca = \frac{R_1 - CQ_1}{CQ_2 - R_2} \qquad (4)$$

$$Ca = \frac{1090 - 1(43)}{1(0.4) - 0.077} = \frac{1047}{0.323} = \underline{3241 \text{ persons}}$$

where:

Q_1 = flow rate from cheese plant

Q_2 = flow rate from community

R_1 = BOD_5 load from cheese plant

R_2 = BOD_5 load from community

Ca = number of persons

C = influent BOD_5 concentration at treatment plant

M_1 = BOD_5 mass, cheese plant

M_2 = BOD_5 mass, community
M_T = total BOD_5 mass
V_1 = flow volume from cheese plant
V_2 = flow volume from community
V_T = total flow volume
t = time

$\therefore$ When whey is <u>not</u> recovered a community of approximately 3 300 persons is needed to ensure that the influent BOD_5 does not exceed 1 000 mg/L. Nutrient supplements of nitrogen and phosphorus will in all likelihood have to be added at the treatment plant.

Because of the wastewater's high biodegradation rate and potentially long transport time in an outfall from a cheese plant to the treatment plant, strong odours are likely to develop. The very high organic load to the treatment plant will also result in substantially increased sludge quantities and associated sludge handling and disposal problems for the community.

One method of reducing the impact on the community's waste treatment facility is to practice some degree of pre-treatment at the cheese plant. Pretreatment at the cheese plant may consist of screening followed by equalization with subsequent continuous discharge to the municipal system.

Any treatment process for the reduction of a high strength waste has a considerable energy input requirement. One exception for a high strength biodegradable waste is the anaerobic digestion process which results in energy extraction from the waste and consequently is a net energy producing process. As well, nutrient requirements and sludge production are considerably less than with other process alternatives. Anaerobic treatment of high strength wastes as a pretreatment step to effluent discharge to a municipal system is fast becoming a viable and attractive process alternative.

It should be noted that municipalities usually levy a sewer surcharge to industry if an industry's waste strength as measured by the BOD_5 exceeds a certain maximum value. In many instances this is 300 mg/L. While the economics of waste treatment are site-specific, it is readily apparent that opportunities for significant cost savings through pretreatment are available.

In any pollution control strategy study, the option of providing complete on-site waste treatment to achieve prevailing effluent standards must be included. On-site treatment processes for whey from cheese production are varied. They range from activated sludge and its many process variations to trickling filters to waste stabilization ponds. Various land irrigation options have also been implemented (7,8,9).

As stated earlier, experience has shown that for **activated sludge** processes to be successful when treating a significant whey load, the influent BOD_5 should be less than 1 000 mg/L. Problems associated with foaming, and bulking have been reported. On the positive side, effluent BOD_5 concentrations of <10 mg/L have been achieved.

It has been reported that **trickling filters** have been more successful in the treatment of whey. However, problems associated with void plugging due to slime formation have been encountered. When successful, effluent BOD_5 concentrations of <25 mg/L have been achieved. In these instances influent BOD_5 dilutions to <300 mg/L were necessary. In northern climates, low ambient temperatures dictate that processes involving thin films (trickling filters, rotating biological contactors) or a high air/liquid interfacial area be designed so that heat losses are minimized. In most instances the expense involved in implementing this measure reduces any process benefits which this alternative may offer.

Waste stabilization ponds for whey treatment, if not artifically aerated, require very large areas and relatively uniform organic load distribution to be effective. It has been reported that whey may lead to protein accumulation on the lagoon floor. This encourages the growth of sulphur-reducing bacteria which bring about H_2S evolution and the associated odour problems. **Aerated lagoons** with influent BOD_5 of 1 000 mg/L have been reported to be capable of producing effluent BOD_5 concentrations of 20 mg/L.

Various modes of land **irrigation** with whey have been reported. In keeping with the concept of re-use, and recognizing that, as a fertilizer, three tonnes of whey contain as much nutrient value as one tonne of manure, the irrigation of agricultural lands with whey is a popular practice. As with all process alternatives, a successful irrigation scheme must meet a series of criteria involving groundwater table, cover, soil permeability, slope, evaporation and proximity to residences, just to name a few.

Methods of irrigation with whey range from spray irrigation, which is practiced more by plants with larger volumes, to broad irrigation (land disposal), to ridge and furrow with a reed canary grass cover. The irrigation of woodlands with whey has also been practiced.

The successful application of any of these methods can result in increased soil fertility and stock-carrying capacity but depends on a variety of factors. Specific prerequisities are soil analyses and a test spraying (application) program. Improper design or application of irrigation technology will result in runoff causing water pollution, and/or ponding causing objectionable odors.

When it comes to pollution control technology it must be recognized that there are no universal solutions. Site-specificity and continually changing economics require that each situation be evaluated separately.

3 THE HYPERFILTRATION PROCESS

The dramatic effects of whey recovery have been illustrated in previous sections. Economic considerations dictate that the recovered whey is best handled in the most concentrated form possible (i.e., minimum volume).

Significant volume reductions can be achieved through solids concentration or thickening processes. This is illustrated mathematically in equation 5, assuming that the mass densities, ρ, of both liquid and solids in the whey are identical:

$$V_f = V_i \left[\frac{100 - mc_i}{100 - mc_f} \right] \tag{5}$$

where: V_f = final volume
V_i = initial volume
mc_i = initial moisture content (%)
mc_f = final moisture content (%)

For example, if the initial moisture content is 94% and the final moisture content is 76%, then the final volume is 25% of the initial volume.

$$V_f = V_i \left[\frac{100 - 94}{100 - 76} \right]$$

$$= V_i \left[\frac{6}{24} \right]$$

$$V_f = 0.25\, V_i$$

Figure 6 illustrates this moisture content-volume reduction relationship.

For effective operation of solids concentration processes, conditioning chemicals to enhance liquid-solid separation must be added in many cases. Since the goal of whey concentration is to produce an unaltered end-product suitable for re-use, addition of chemicals is inappropriate. Membrane processes offer a technology which results in the concentration of solids through molecular sieving under a driving force. Chemicals to enhance the efficiency of liquid-solids separation are not added.

3.1 Membrane Technology

As the terminology implies, liquid-solid separation is achieved by using a membrane which acts as a barrier to the flow of molecular or ionic species between the phases that it separates. Membranes can be manufactured to a variety of specifications

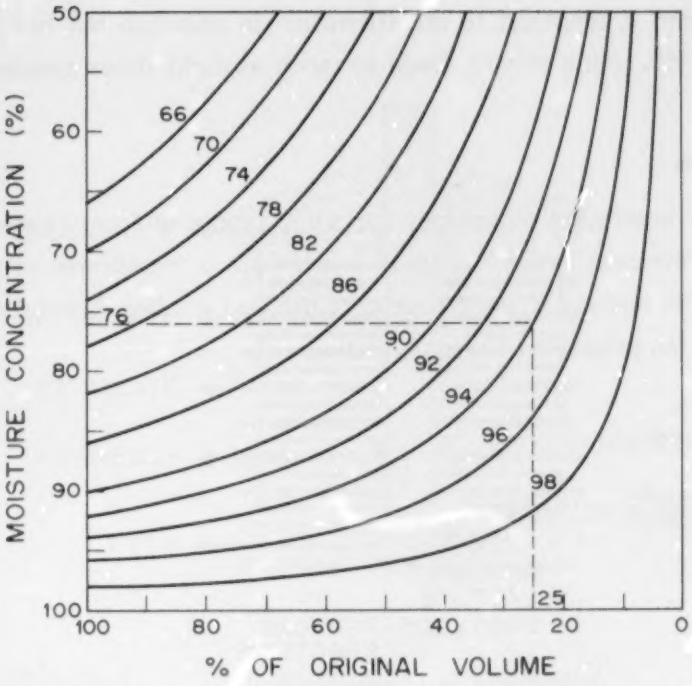


FIGURE 6 MOISTURE CONTENT - VOLUME REDUCTION RELATIONSHIP

TABLE 9 MAJOR MEMBRANE PROCESSES

Process		Membrane Function	Principal Driving Force
1.	Electrodialysis	selective ion transport	electrical potential
2.1	Ultrafiltration	selective transport of large molecules	pressure (low)
2.2	Hyperfiltration	selective transport of small molecules	pressure (high)
3.	Reverse Osmosis	selective transport of water	pressure (highest)

making them highly permeable for some species and low for others. Generally speaking there are three major membrane processes as shown in Table 9.

Electrodialysis finds its major application in desalting brackish water, whereas reverse osmosis is used not only for desalting of brackish water but for the removal of organic species as well. As indicated in Table 9 ultrafiltration technology involves the separation of macromolecules (molecular weights in the 6 000-65 000 range). The

membrane is also designed to pass or reject molecular species on the basis of shape and chemical structure. Hyperfiltration is identical to ultrafiltration in principle but has a low molecular weight cut-off of 500, and a driving force as much as eight times greater than for ultrafiltration.

3.2 Hyperfiltration Systems

In applying membrane separation technology for whey produced from cheese manufacturing operations, hyperfiltration is used because it provides a membrane with pore size so that molecules of >500 molecular weight are retained and smaller molecules pass through. Figure 7 illustrates the principle of hyperfiltration.

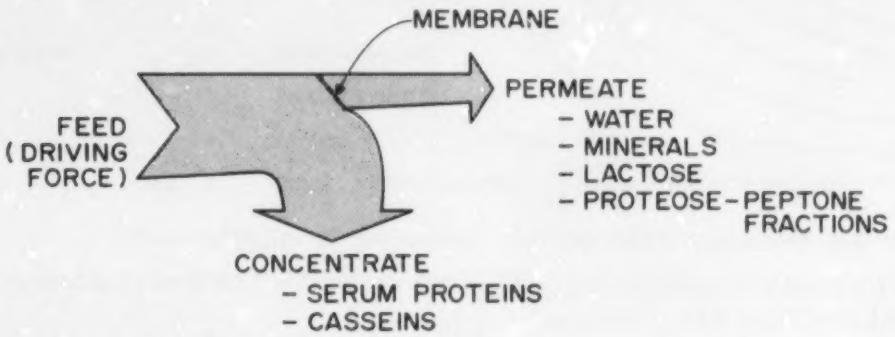


FIGURE 7 FEED SEPARATION THROUGH HYPERFILTRATION

As shown in Figure 7 the feed is split into a permeate and a concentrate fraction. Because of their large molecular weight the serum proteins and caseins are retained in the concentrate whereas the permeate contains water, minerals, lactose and proteose-peptone fractions.

Hyperfiltration systems are commercially available in two standard sizes, one that can operate at pressures of up to 8 000 kPa, the other at pressures of up to 5 000 kPa. The designs are the same, with membranes stacked in vertical modules in a spacer/membrane covered plate arrangement assembled in sandwich fashion. The stack of spacers, plates and membranes is hydraulically compressed so that thin membrane-covered flow channels are created. During operation, as shown in Figure 8, the flow is split in two. One stream is called permeate, which passes through the membrane (Figure 7); the other is rejected by the membrane and is called concentrate.

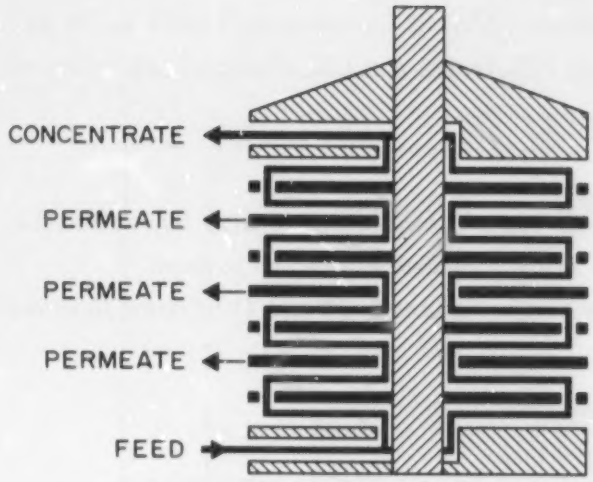


FIGURE 8 HYPERFILTRATION MODULE SCHEMATIC

For whey it is the concentrate which may then be:

a) incorporated into food products,
b) further processed (by evaporation) to powder, or
c) fed to animals where reduced transportation costs and higher feed/water values are important considerations.

The permeate could be reused in the plant as washwater (first flush of tanks and pipelines), or discharged to a sewer for treatment.

4 PROCESS EQUIPMENT AND OPERATION

The hyperfiltration system used for the study program at La Fromagerie d'Oka was manufactured by Dedanske Sukkerfabrikker (DDS) of Copenhagen, Denmark. It was originally supplied by a Canadian distributor, J.E. Trudel and Co., Montreal, at a cost of $220 000 (1978).

4.1 Process Description

The heart of the hyperfiltration system consists of 6 DDS hyperfiltration modules with polypropylene membranes fed by a high pressure pumping system.

The equipment arrangement is shown in Figures 9, 10 and 11. Figure 10 shows a single hyperfiltration module.

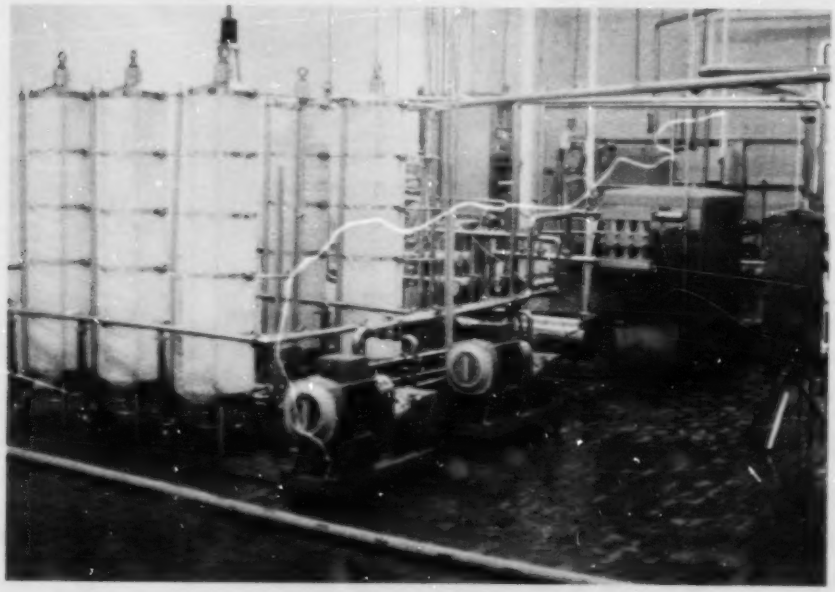


FIGURE 9 HYPERFILTRATION SYSTEM LAYOUT

4.2 General System Operation

The following is a description of the whey concentration process as shown in Figure 11.

Raw whey is taken from cheese oats at 35°C and pumped to a holding tank [1]. From the holding tank the whey is passed over a vibratory screen (200 mesh) [2] to remove

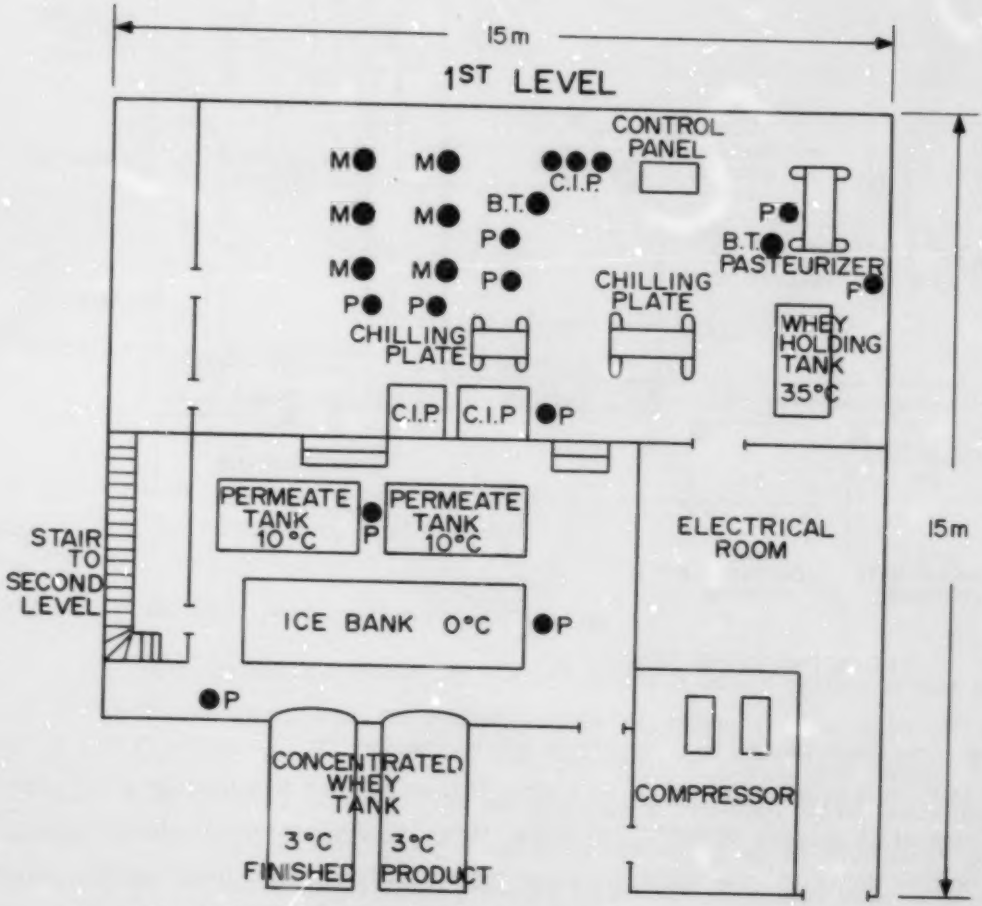


FIGURE 10 LAYOUT OF BUILDING AND EQUIPMENT

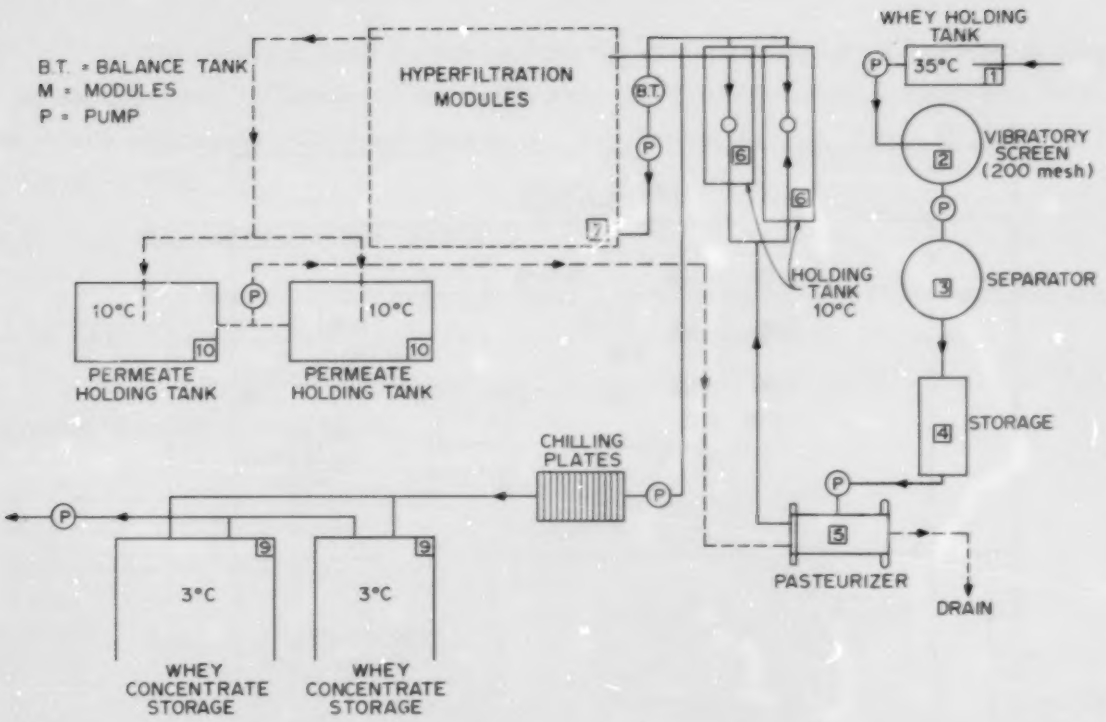


FIGURE 11 PROCESS FLOW DIAGRAM

curds. The whey then passes to a separator [3] where the fat content is reduced from ±0.6% to ±0.01% and briefly stored [4]. The whey is then pumped to a pasteurizer [5] for a residence time of 16 seconds at 108°C, cooled to 10°C and discharged to holding tanks [6]. From the holding tanks [6] the hyperfiltration system is run in the batch mode. Upon start-up (usually 0800-0900 hours) the whey is pumped continuously to the hyperfiltration system [7] from the holding tanks [6] until the solids concentration reaches 24%. The whey concentrate is then cooled [8] to approximately 3°C and held in storage for shipment [9]. The permeate from the hyperfiltration modules [7] is collected in holding tanks at 10°C [10].

The hyperfiltration system consists of six modules operated as two groups of three modules arranged in series. Each of the three-module arrangements in turn is in a parallel configuration (Figure 12).

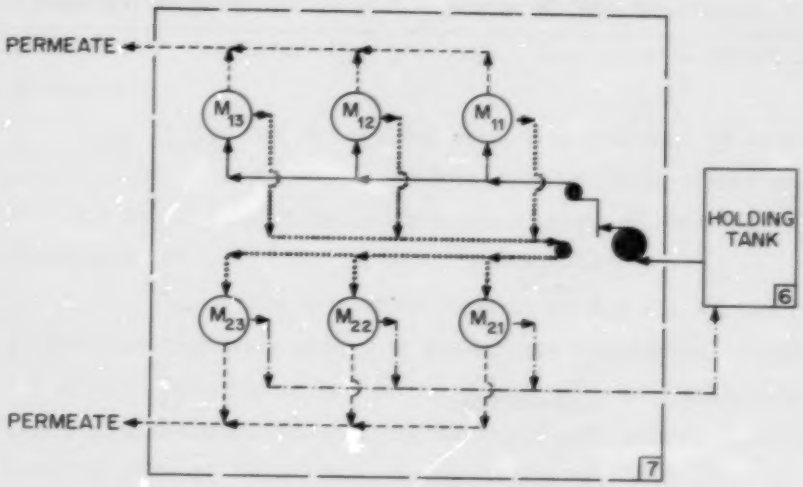


FIGURE 12 HYPERFILTRATION MODULE ARRANGEMENT
(open-loop feed system)

4.3 Rated Hyperfiltration Plant Capacity

The system specifications (Table 10) cite a design permeate rate of 1 010 L/h per three-module group with an overall volumetric concentration ratio of 4:1. With a total surface area of 84 m^2 (3 x 28 m^2) per module group, the design flux rate is 1 010 L/h ÷ 84 m^2 = 12 L/m^2•h. The system uses a two-step pressure configuration. It consists of one high-pressure pump capable of delivering up to 5000 kPa* pressure. A booster pump increases the system pressure by an additional 600 kPa. The concentrate leaving the first module group has experienced a 600 kPa pressure drop through the system. Thus a second booster pump to make up for this pressure drop is required. This ensures that the pressure for each module group is the same.

4.4 System Specifications

The technical data for the hyperfiltration system studied is summarized in Table 10.

---

* The equipment used was actually gauged in bars; 1 bar = 100 kPa.

TABLE 10 SYSTEM TECHNICAL DESCRIPTION

Description	Units	Specification
DDS Hyperfiltration system:		
Feed:		
type	-	sweet whey
total solids	%	6
pH	-	6
temperature	°C	30
hydraulic rate	L/h•module	448
system flux	$L/m^2 \cdot h$	16
Concentrate:		
temperature	°C	30
hydraulic rate	L/h•module	111
total solids	%	24
Permeate:		
hydraulic rate	L/h•module	337
flux	$L/m^2 \cdot h$	12
Power consumption	kW	8
Water consumption	m^3/d	5
Cooling requirement	kcal/h	6 900
Power	-	3 x 550V, 60 Hz
Pressurized Air	atm.	5
Cooling water	°C	2
Module Type:		40-28-4
membrane type	-	990
membrane material	-	cellulose acetate
membrane area	m^2/module	28

4.5 Start-up

The major problem experienced during start-up (June 1979) concerned the seals for the booster pumps. Not only were the seals found to be extremely delicate, but they were also difficult to install. The experience at La Fromagerie d'Oka was that seal failure resulted in complete hyperfiltration process shut-down for extended periods. During the period from August 1979 - November 1979 seal failure occurred at least five times.

From December 1979 - March 1980 problems concerning the aquisition of replacement seals had the whole system shut down. The manufacturer replaced his Canadian representative with General Dairy Equipment Co. of Minneapolis, which immediately corrected the problem. The hyperfiltration system remained on line thereafter.

It was not recognized that it is essential to keep the membranes moist by circulating a disinfectant at all times. During the first shut-down period of six weeks this was not done. As a consequence approximately 50 membranes developed holes and had to be replaced.

During the first three to four months the booster pump gear boxes developed problems, which were traced to inadequate lubrication. Figure 13 illustrates the failed bearings. The oil used had to be altered with an additive specially developed (General Dairy Equipment of Minneapolis) for this short coming. This has extended the life of the bearings. The oil though must be checked daily.

FIGURE 13 FAILED BEARINGS IN BOOSTER PUMP GEAR BOX

While the original recommended time for system cleaning with TERGAZYME was 90 minutes, it was determined that this was inadequate. Increasing the cleaning time

to 120 minutes resulted in increased membrane efficiency, to the point where the initial membrane fluxes did not vary from day to day.

4.6 Operator Requirements

Even though the hyperfiltration system consists of a number of sophisticated components, it was found that the operator at La Fromagerie d'Oka was able to run the system after two days indoctrination by the manufacturers' representative.

A number of factors important to the successful operation of a hyperfiltration system are as follows:

1) The supplier must explain how the system functions.
2) The supplier must demonstrate how components are assembled and disassembled.
3) An operating chart must be developed to assist the operator in running the system.
4) A stock of replacement parts for critical components must be kept at the plant, and others with supplier but available on short notice.
5) The operator need not have technical qualifications obtained through special training, but must have some mechanical aptitude.

It should be noted that all operational cycles for the hyperfiltration system including cleaning are handled automatically through a pre-programmed control module. No difficulties were experienced in this regard.

4.7 Additional Observations

The Fromagerie d'Oka experience was that the booster pump seals only last approximately three months. If one set of seals fail then both sets should be replaced. It was also observed that the chance of membrane blow-out occurring was greatly increased at pressures greater than 4200 kPa.

Membrane life was less than expected, i.e., six months vs. 12-14 months. Neckrings must also be used when replacing membranes. In takes approximately one day to change one membrane stack.

5 DEMONSTRATION PROGRAM MONITORING AND RESULTS

The demonstration program was designed to assess the practicability and economics of sweet whey concentration through hyperfiltration technology. One interesting aspect of this study was that the hyperfiltration plant would be run by existing personnel, with analytical support from their laboratory staff. The reason for this was to establish whether or not the degree of process complexity would require special operating skills.

The overall process schematic is shown in Figure 14.

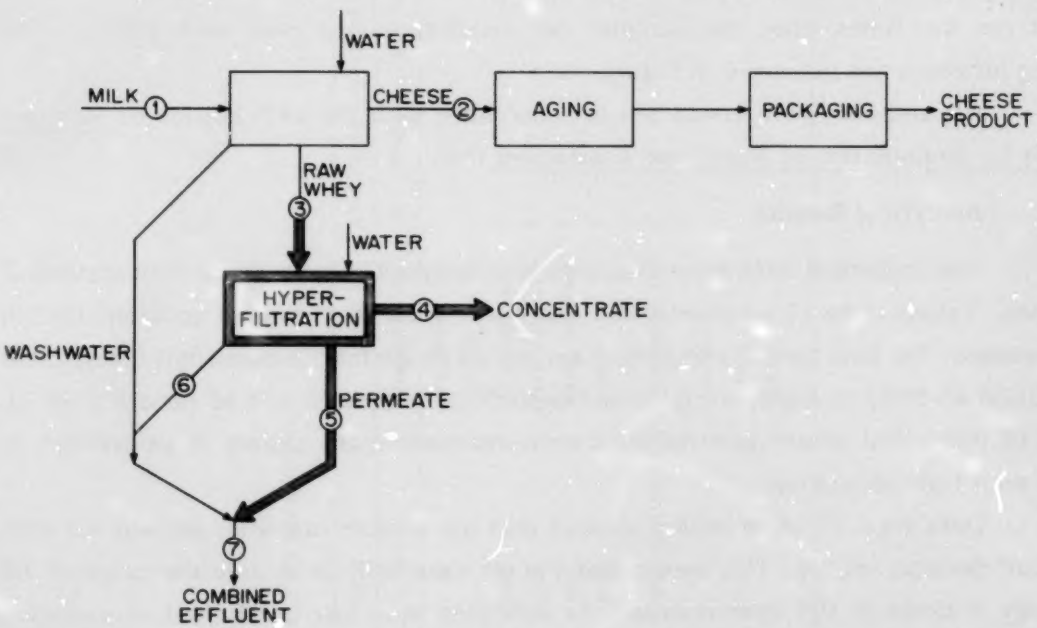


FIGURE 14 OVERALL PROCESS SCHEMATIC AT LA FROMAGERIE D'OKA

The process demonstration program started on June 19, 1979 and continued for the next 592 days until January 30, 1981. During this time three significant periods of process shut-down occurred:

a) day 46 - day 114,

b) day 148 - day 258,

c) day 400 - day 426 (intermittent operation).

Since the system was batch-operated (daily) for five consecutive days, the actual system down time was 34%. Factors responsible for this inordinately high down time were cited in the previous section.

A summary of the monitoring and analyses schedule is shown in Table 11. During the course of the program ancillary studies were conducted to determine the optimum operating pressure and membrane rejection characteristics.

5.1 Sampling and Analyses

Single grab samples were taken for the various parameter analyses. Table 12 summarizes the times when the samples for constituent analyses were taken. The sampling locations are indicated on Figure 14.

All analyses were conducted in accordance with the 14th edition of Standard Methods for Examination of Water and Wastewater (10).

5.2 Analytical Results

The analytical data were examined and analyzed in accordance with statistical principles. Tables 13 to 17 summarize the analytical data. It is readily apparent that in most instances the data for all parameters except pH range from inconsistent (coefficient of variation 40-59%) to highly variable and unpredictable (coefficient of variation $\geq$60%). In light of this initial observation the data were examined more closely in an attempt to explain their high variability.

Data from 45 observations showed that the median raw whey pH was 6.2 with a standard deviation of 0.6. This means that the pH value will be outside the range of 5.0 - 7.4 only 5 times in 100 observations. As indicated by a low coefficient of variation (CV = 9%) the data show a high degree of consistency.

The ammonia data are highly variable and unpredictable (CV = 61%). The median concentration is 113 mg/L; the distribution is not normal.

The COD data appear to be inconsistent. This can be attributed to a few extremely high and a few very low values. For example, the lowest recorded value was 21 000 mg/L and the highest was 280 000 mg/L. The raw whey is relatively consistent in quality and as such should exhibit consistent (normal distribution) characteristics. The inconsistencies have been attributed to sampling error. By deleting COD values of $\leq$47 000 mg/L and $\geq$93 000 mg/L and using the remaining 44 observations, a normal

TABLE 11 PROCESS MONITORING AND ANALYSES PROGRAM

No.	Parameter	Units	Measurement		Type		Whey Related Characteristics								
			Frequency	Quantity	Sample	Measurement	pH	BOD_5	COD	NH_3-N	TS	SS	VS	E.Coli	F.Coli
1	Milk	kg/d	daily	-	-	production									
2	Cheese	kg/d	daily	-	-	records									
3	Raw whey	kg/d	daily	2/wk	grab	float measured	*	*	*	*	*	*	*	*	*
4	Conc. whey	kg/d	daily	2/wk	grab	float measured	*	*	*	*	*	*	*	*	*
5	Permeate	kg/d	daily	2/wk	grab	by difference	*	*	*	*	*	*	*	*	*
6	Washwater	m^3/d	as used	2/wk	grab	meter	*	*	*	*	*	*	*	*	*
7	Combined effluents	m^3/d	daily	2/wk	sporadic composite	summation 5.+6.	*	*	*	*	*	*	*	*	*
8	Pressure system	kPa	hrly	-	-	visual									
9	System temp.	°C	hrly	-	-	visual									
10	Rotameter Reading	%	hrly	-	-	visual									

TABLE 12 SAMPLING TIMES

Sample	Sample Time
Raw whey	at beginning of run
Concentrate	at end of run
Permeate	at end of run
Washwater	at end of run
Total Effluent	at end of run

distribution with a coefficient of variation of 7.5% was obtained (Figure 15). With a mean COD of 64 000 mg/L, one can be certain that the COD value would be outside the range of 54 400 - 73 600 mg/L in only 5 out of 100 observations.

It is quite normal to find that BOD_5 determinations suffer from considerable variability, especially in the case of high BOD_5 concentrations. Thus it was interesting to see that this expected high degree of variability did not materialize (Figure 16). Nevertheless, extremely low values (two) of 14 000 mg/L and less, and extremely high values (three) of 40 000 mg/L and more were deleted from the analysis. The coefficient of variation improved from 20% to 13%. Deletion of these values was judged to be fully justified on the basis of the raw whey COD/BOD_5 ratio. Using 41 observations the mean BOD_5 raw whey concentration was calculated to be 29 500 mg/L. In 100 observations, 5 will be outside the range of 21 700 - 37 300 mg/L (Figure 17).

A useful parameter in environmental engineering is the COD/BOD_5 ratio. A highly biodegradable waste will have a low COD/BOD_5 ratio whereas a bioresistant waste will exhibit a high COD/BOD_5 ratio. Upon examining the raw data and calculating the appropriate COD/BOD_5 ratios, the ratios were determined to vary from 0.72 to 6.36. The distribution of data is not normal. Again, a raw whey should exhibit a relatively constant COD/BOD_5 ratio and be normally distributed. For reasons noted under the COD and BOD_5 discussion, ratios less than 1.5 and greater than 3 were deleted from further analyses. The data are shown in Figure 18 and indicate a mean COD/BOD_5 ratio of 2.22 with a coefficient of variation of 15%. Five out of 100 ratios are expected to lie outside the range 1.54 - 2.90. The calculated average COD/BOD_5 ratio based on the mean COD and BOD_5 values described earlier was 2.17.

TABLE 13 RAW WHEY CHARACTERISTICS

Parameter	Unit	$\bar{x}$	σ	$\bar{x}+\sigma$	$\bar{x}-\sigma$	n	CV*
pH	-	6.22	0.57	6.79	5.65	45	9
NH_3-N**	mg/L	113.3	68.7	182	44.6		61
COD[1]	mg/L	67 022	36 298	103 320	30 724		54
BOD_5	mg/L	29 689	6 171	35 860	23 518		21
TS	mg/L	61 389	3 845	65 234	57 544		6
VS	mg/L	357	242	699	115		68
SS	mg/L	529	549	1 078	--		>100
E. Coli	per 100 mL	68 526	48 455	--	--		71
F. Coli	per 100 mL	43 489	49 175	--	--		>100
COD/BOD_5	-	2.26					

* CV
- ≤ 19 Highly consistent
- 20-39 Fairly consistent
- 40-59 Inconsistent
- ≥ 60 Highly variable and unpredictable

** Not normally distributed

The raw whey total solids data were almost normally distributed. It was decided though that total solids concentrations of less than 4.7% should be deleted from further analyses. This decision was based on observation of the initial probability distribution for the total solids data. Deletion of six low values changed the mean total solids concentration from 6.11% to 6.24%. The degree of data variability was reduced by a factor of two. The data as shown in Figure 4 show that 5 out of 100 observations will be greater than 6.7% or less than 5.8%. The raw whey solids concentration of 6.2% only slightly exceeds the process design value of 6.0%. This is of little consequence.

The raw whey suspended solids (SS) and volatile solids (VS) data were highly variable and unpredictable (CV >100% and >68%, respectively). The SS concentration varied from a low of 64 mg/L to a high of 3 600 mg/L, whereas the VS varied from 90 mg/L to 1 530 mg/L. For the purposes of this investigation these parameters were judged to be inconsequential.

TABLE 14 WHEY CONCENTRATE CHARACTERISTICS

Parameter	Unit	$\bar{x}$	σ	$\bar{x}+\sigma$	$\bar{x}-\sigma$	n	CV*
pH	-	6.26	0.26	6.52	6.00	45	4
NH_3-N**	mg/L	430	306	736	124		71
COD	mg/L	218 180	89 018	307 198	129 162		41
BOD_5	mg/L	104 330	28 790	133 120	75 540		28
TS**	mg/L	262 980	81 832	344 812	181 148		31
VS	mg/L	1 247	793	2 040	454		64
SS	mg/L	2 301	6 707	9 008	--		>100
E. Coli	per 100 mL	53 160	46 676	--	--		88
F. Coli	per 100 mL	11 937	31 586	--	--		>100
COD/BOD_5	-	2.09					

* CV ≤ 19 Highly consistent
20 - 39 Fairly consistent
40 - 59 Inconsistent
≥60 Highly variable and unpredictable

** Not normally distributed

Bacteriological analyses of the raw whey indicated contamination. For example, 47 out of 57 samples showed counts as high as 1.1×10^5 for E. coli. Only 10 samples show an E. coli count of zero. The data for F. coli was not much better. Eighteen out of 57 samples had a count of zero; 21 had counts exceeding 10^5.

Analytical parameters for whey concentrate, permeate, washwater and total effluent are, as noted earlier, summarized in Tables 14 to 17. Most are of lesser importance in this particular study but will be referred to in specific discussions of the parameters in subsequent sections of this report. Total solids concentrations and bacterial count are important parameters in the concentrate because they affect reuse options.

TABLE 15 PERMEATE CHARACTERISTICS

Parameter	Unit	$\bar{x}$	σ	$\bar{x}+\sigma$	$\bar{x}-\sigma$	n	CV*
pH	-	5.83	0.58	6.41	5.25	46	10
NH_3-N**	mg/L	14.3	14.4	28.7	-		>100
COD**	mg/L	1 081	1 024	2 105	57		95
BOD_5**	mg/L	612	585	1 197	27		96
TS**	mg/L	1 783	1 138	2 921	645		64
VS	mg/L	10.5	15.4	25.9	--		>100
SS	mg/L	17.3	18.2	35.5	--		>100
E. Coli	per 100 mL	16 996	33 864	--	--		>100
F. Coli	per 100 mL	57	205	00	00		>100
COD/BOD_5	-	1.76					

* CV ≤ 19 Highly consistent
20-39 Fairly consistent
40-59 Inconsistent
≥60 Highly variable and unpredictable

** Not normally distributed

TABLE 16 WASHWATER CHARACTERISTICS

Parameter	Unit	$\bar{x}$	σ	$\bar{x}+\sigma$	$\bar{x}-\sigma$	n	CV*
pH	-	6.53	0.50	7.03	6.03	38	8
NH_3-N	mg/L	2.77	8.82	11.59	--		>100
COD	mg/L	3 042	1 345	4 387	1 697		44
BOD_5	mg/L	1 596	684	2 280	912		43
TS	mg/L	8 854	2 120	10 974	6 734		24
VS	mg/L	13.7	12.4	26.1	1.3		91
SS	mg/L	16.5	12.3	28.8	4.2		75
E. Coli	per 100 mL	3	7				>100
F. Coli	per 100 mL	2	7				>100
COD/BOD_5	-	1.91					

* CV ≤ 19 Highly consistent
20-39 Fairly consistent
40-59 Inconsistent
≥60 Highly variable and unpredictable

TABLE 17 TOTAL EFFLUENT CHARACTERISTICS

Parameter	Unit	$\bar{x}$	σ	$\bar{x} + \sigma$	$\bar{x} - \sigma$	n	CV*
pH	-	6.36	0.13	6.49	6.23	9	2
NH_3-N	mg/L	5.72	1.56	7.28	4.16	5	27
COD	mg/L	7 911	4 070	11 981	3 841	9	51
BOD_5	mg/L	3 267	1 819	5 086	1 448	9	56
TS	mg/L	6 044	3 375	9 419	2 669	9	56
SS	mg/L	556	217	773	339	9	39
VS	mg/L	483	199	682	284	9	41
COD/BOD_5	-	2.42					

* CV
- ≤ 19 Highly consistent
- 20-39 Fairly consistent
- 40-59 Inconsistent
- ≥ 60 Highly variable and unpredictable

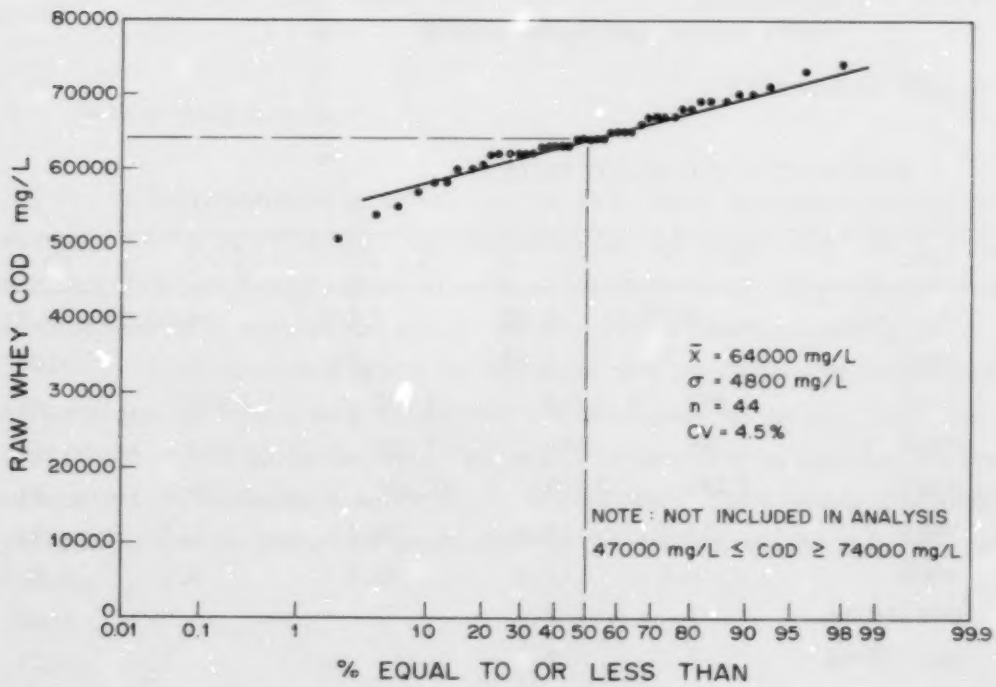


FIGURE 15 RAW WHEY COD DISTRIBUTION

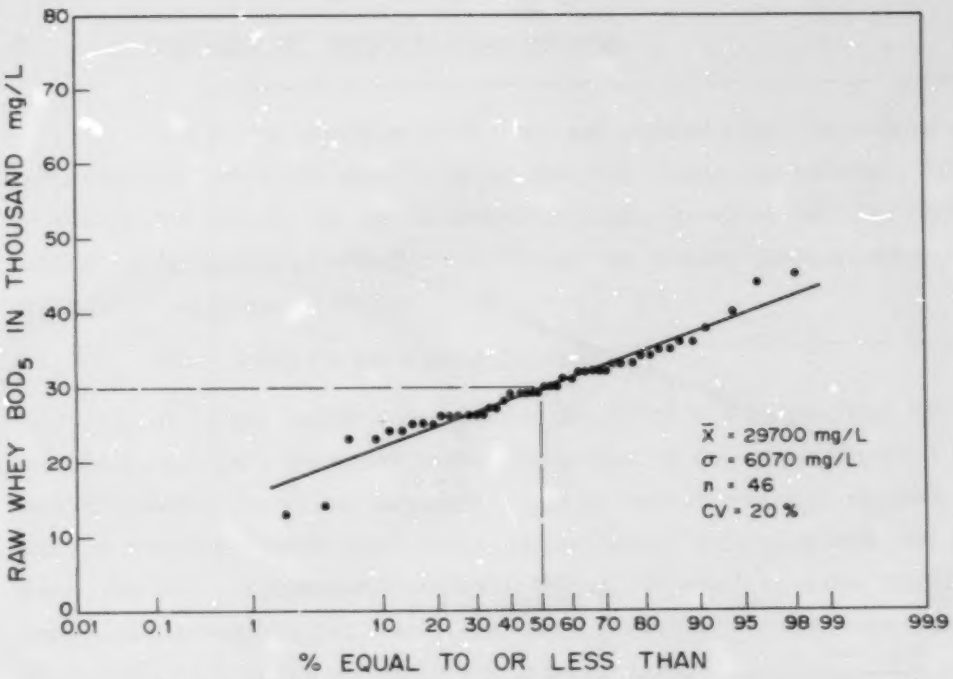


FIGURE 16 RAW WHEY BOD_5 DISTRIBUTION

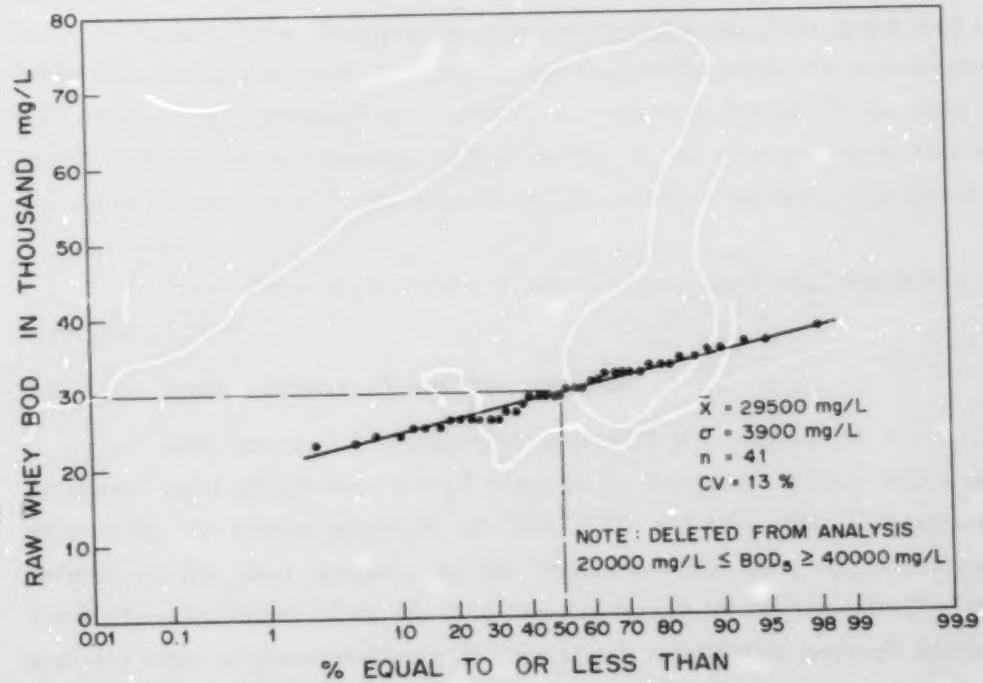


FIGURE 17 RAW WHEY BOD_5 DISTRIBUTION (adjusted)

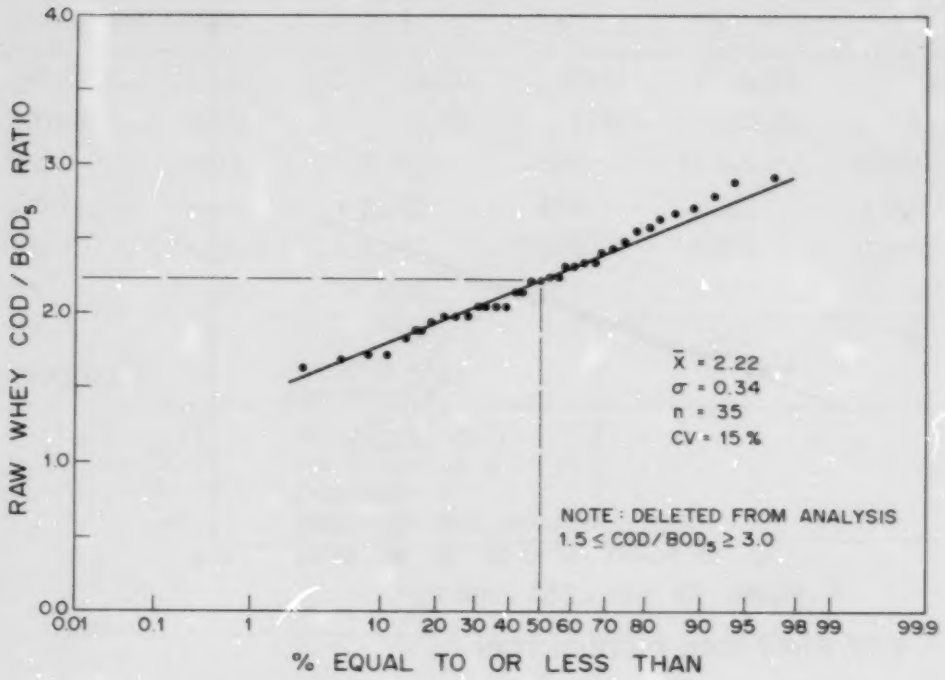


FIGURE 18 RAW WHEY COD TO BOD_5 RATIO DISTRIBUTION

6 TECHNICAL PROCESS EVALUATION

The prime objective from a process point of view was to determine the solids concentration capability and limits of this hyperfiltration system. Ancillary studies addressed the search for an optimum operating pressure and its relation to solids concentrating ability, system flux determinations, process water requirements and membrane rejection characteristics.

6.1 Whey Solids Concentrating Capability

A target solids concentration factor of 4 was specified by the equipment manufacturer. Data examination over the period of the demonstration run showed that only 27 concentrate values out of 36 could be used in any data analysis. For example, early in the study concentrate solids concentrations exceeding 46% and as low as 10% were reported. Clearly, this could not be so. A check revealed that an error in the analytical methodology had been made. After correction, further whey concentrate solids values were more in line with what was to be expected.

To assess the solids concentration performance, the 27 remaining values were subjected to statistical analysis. The mean solids concentration factor as determined from the ratio of concentrate solids to raw whey solids was 3.9. This indeed is remarkable when considering the errors in sampling and analysis for solids for both fractions. Perhaps fortuitously they cancelled each other. As shown in Figure 19 the data are normally distributed and highly consistant (CV = 13.4%). It can be stated with 95% certainty that the solids concentration factor is between 2.8 and 4.9. The design specification called for a factor of 4.

From these observations it would appear then that the solids concentration objective was met.

6.2 System Pressure/Solids Concentration

One series of investigations addressed the question of how different system pressures might affect the rate of whey solids increase. Hourly solids determinations were made for system pressures of 3000, 3700 and 4200 kPa. The system pressure is defined as the inlet pressure to the modules. The data for the various runs are summarized in Tables 18 to 20. The average hourly solids concentration was plotted on semi-log paper as shown in Figure 20. A distinct relationship between operating time and

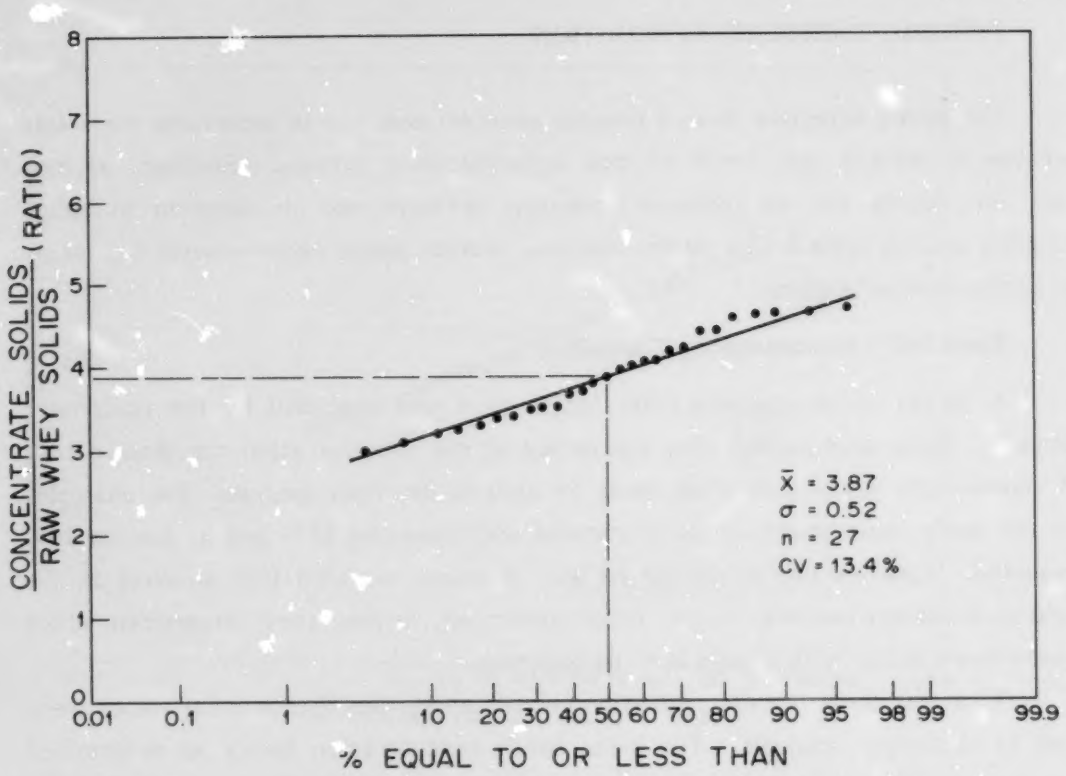


FIGURE 19 CONCENTRATE TO RAW WHEY SOLIDS DISTRIBUTION

solids concentration exists. Not unexpectedly, the rate of solids concentration increase is greater with higher system pressures up to a specific time; the rate of solids increase then decreases. The higher the system pressure, the earlier this change in slope occurs. This can be attributed to the forcing of higher molecular weight solids through the membrane rather than being able to take advantage of interferences caused at the membrane surface due to the presence of a lower force field.

Solids concentrations of 12% and less can be attained more rapidly at 4200 kPa than at either 3700 or 3000 kPa. For solids concentration targets of greater than 12%, a system operating pressure of 3700 kPa is optimum.

The three functions can be described mathematically by the equations summarized in Table 21. It should be noted that, except for optimum pressure determination, after a rapid initial increase in solids concentration at higher operating pressure, maximum solids concentrations are attained at lower system pressures. This is

TABLE 18 SOLIDS CONCENTRATION EFFECT AT 3000 kPa

Pressure (kPa)	Time (h)	Solids Concentration (%)				
		12/1/81	13/1/81	14/1/81	16/1/81	Average
3000	0	6.59	5.97	6.19	5.67	6.1
	1	7.87	7.36	7.21	6.31	7.2
	2	8.22	7.44	7.63	7.10	7.6
	3	9.10	8.10	8.74	-	8.6
	4	10.58	8.82	9.87	8.95	9.6
	5	12.42	9.45	11.46	9.54	10.7
	6	14.09	12.34	12.71	12.34	12.9
	7	16.25	14.17	14.86	14.58	15.0
	8	16.55	16.50	15.93	16.45	16.4
	9	18.91	19.80	18.32	19.74	19.2
	10	21.41	20.87	18.89	20.82	20.5
	11	23.30	21.97	20.10	23.36	22.2
	12	23.69	22.56		25.80	24.0
	13	24.35			25.79	25.1

of little practical significance at this time since hyperfiltration systems operate at constant, preset pressures.

The equations shown in Table 21 can be used to predict the time when a specified solids concentration is reached when operating the system at a specific pressure. Solutions to equations 7, 9, 11, 13, 15 and 17 are summarized in Table 22. The data show that no advantage is gained by operating the system at 4200 kPa. Operation at 4200 kPa appears to require a longer time to attain solids concentrations of 18 and 24% than operation at 3700 kPa.

It was observed that an operating pressure of 3700 kPa appears to give optimum results. However, if the same result could be achieved at a lower operating pressure but slightly longer time, some savings due to reduced energy consumption might be achieved. Figure 21 was constructed to determine how much operator time could be saved if the system were operated at 3700 rather than 3000 kPa. Clearly in this

TABLE 19 SOLIDS CONCENTRATION EFFECT AT 3700 kPa

Pressure (kPa)	Time (h)	Solids Concentration (%)			
		19/1/81	20/1/81	21/1/81	Average
3700	0	5.93	5.42	5.91	5.8
	1	6.92	6.33	6.56	6.6
	2	8.41	7.66	8.23	8.1
	3	8.93	8.82	9.72	9.2
	4	8.97	10.60	11.39	10.3
	5	12.37	12.25	13.44	12.7
	6	14.53	14.00	17.42	15.3
	7	15.06	16.67	18.84	16.9
	8	19.74	18.94	19.18	19.3
	9	22.24	19.99	19.17	20.5
	10	22.67	21.36		22.0
	11	26.02	21.69		23.9

TABLE 20 SOLIDS CONCENTRATION EFFECT AT 4200 kPa

Pressure (kPa)	Time (h)	Solids Concentration (%)			
		26/1/81	27/1/81	30/1/81	Average
4200	0	5.55	5.64	5.64	5.6
	1	6.35	6.97	7.11	6.8
	2	8.52	7.94	8.67	8.4
	3	10.35	9.90	10.25	10.2
	4	11.69	10.93	11.68	11.4
	5	13.90	12.49	13.70	13.5
	6	15.80	13.92	15.88	15.2
	7	18.88	15.34	16.16	16.8
	8	19.50	16.43	16.28	17.4

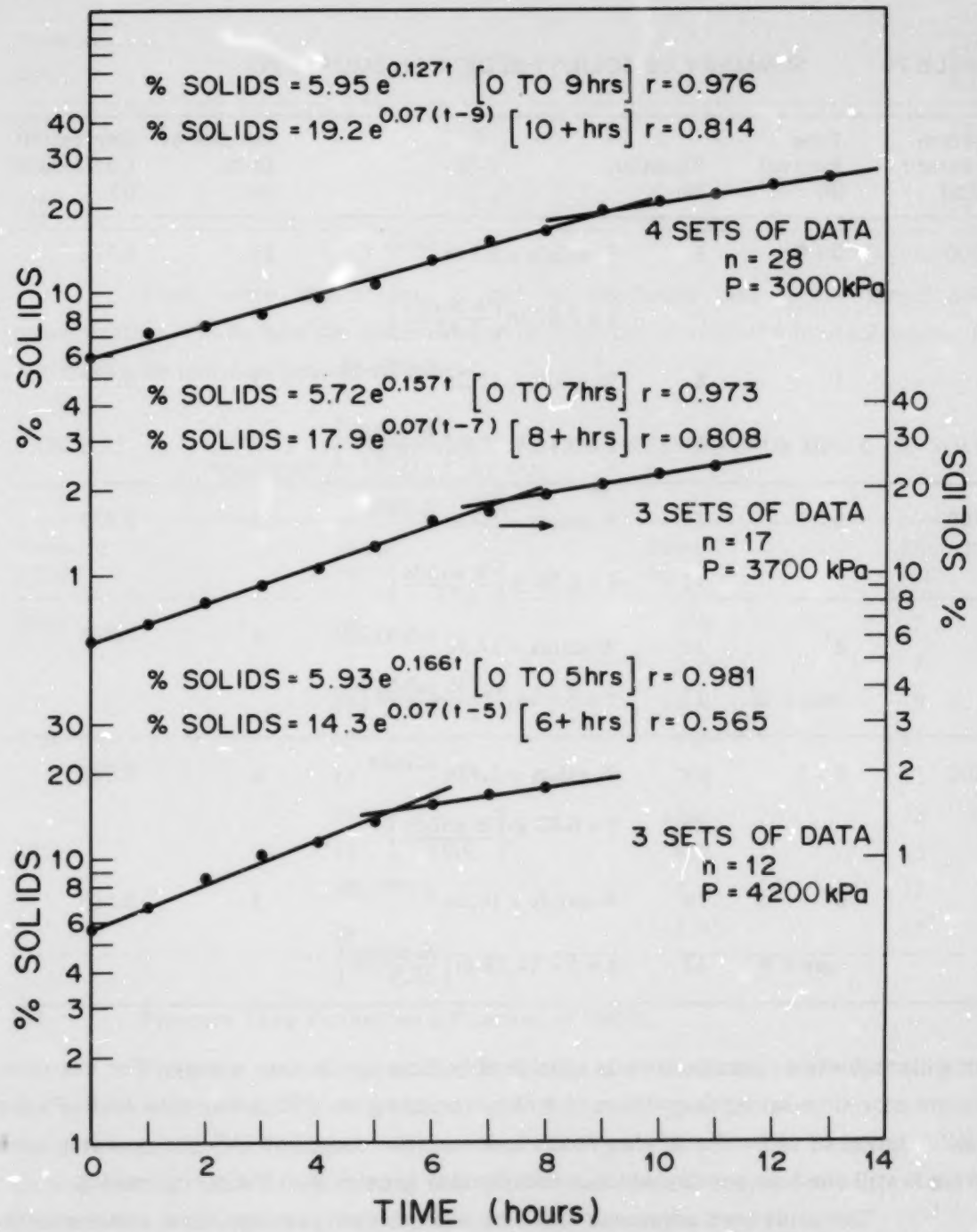

% SOLIDS = 5.95 e^0.127t [0 TO 9hrs] r = 0.976
% SOLIDS = 19.2 e^0.07(t-9) [10 + hrs] r = 0.814
4 SETS OF DATA
n = 28
P = 3000kPa
% SOLIDS = 5.72e^0.157t [0 TO 7hrs] r = 0.973
% SOLIDS = 17.9e^0.07(t-7) [8+ hrs] r = 0.808
3 SETS OF DATA
n = 17
P = 3700 kPa
% SOLIDS = 5.93e^0.166t [0 TO 5hrs] r = 0.981
% SOLIDS = 14.3e^0.07(t-5) [6+ hrs] r = 0.565
3 SETS OF DATA
n = 12
P = 4200 kPa
% SOLIDS
% SOLIDS
TIME (hours)

FIGURE 20 SOLIDS CONCENTRATION AS A FUNCTION OF TIME AND PRESSURE

TABLE 21 SUMMARY OF SOLIDS PREDICTION EQUATIONS

System Pressure (kPa)	Time Interval (h)	Equation No		Number of Data (n)	Regression Coefficient (r)
3000	0 - 9	6	$\% \text{ solids} = 5.95e^{0.127t}$	10	0.976
		7	$t = 7.87 \ln\left[\frac{\% \text{ solids}}{5.95}\right]$		
	10^+	8	$\% \text{ solids} = 19.2e^{0.07(t-9)}$	5	0.814
	max = 14	9	$t = 9 + 14.28 \ln\left[\frac{\% \text{ solids}}{19.2}\right]$		
3700	0 - 7	10	$\% \text{ solids} = 5.72e^{0.157t}$	8	0.973
		11	$t = 6.34 \ln\left[\frac{\% \text{ solids}}{5.72}\right]$		
	8^+	12	$\% \text{ solids} = 17.9e^{0.07(t-7)}$	4	0.808
	max = 12	13	$t = 7 + 14.28\left[\frac{\% \text{ solids}}{17.9}\right]$		
4200	0 - 5	14	$\% \text{ solids} = 5.93e^{0.166t}$	6	0.981
		15	$t = 6.02 \ln\left[\frac{\% \text{ solids}}{5.93}\right]$		
	6^+	16	$\% \text{ solids} = 14.3e^{0.07(t-5)}$	3	0.565
	max = 9	17	$t = 5 + 14.28 \ln\left[\frac{\% \text{ solids}}{14.3}\right]$		

particular situation operator time is considerably more costly than energy. For example, the operator time saving is optimum (1.4 h) by operating at 3700 rather than 3000 kPa for a solids target of 18%. For a whey solids concentration target of 24% the operator time saving is still one hour per day which is considerably greater than the energy saving.

The total cost advantage still lies with shorter operator time requirements. Figure 21 illustrates these effects.

The equations shown in Table 21 can also be shown as a family of curves (Figure 22). From this figure it would appear that maximum solids concentrations can be attained as follows:

Pressure (kPa)	S_{max} (%)	Time (h)
3000	23.7	12
3700	25.4	12
4200	23.3	12

From these observations it can be concluded that if the target solids concentration is 24%, then the system should be operated at 3700 kPa for 11.2 hours. This represents the optimum process condition.

TABLE 22 EFFECT OF DIFFERENT SYSTEM PRESSURES ON RATE OF SOLIDS CONCENTRATION INCREASE

Pressure (kPa)	Solids (%)	Time (h)	Equation No.
3000	12	5.5	7
	18	8.7	7
	24	12.2	9
3700	12	4.7	11
	18	7.3	13
	24	11.2	13
4200	12	4.2	15
	18	8.3	17
	24	(12.4)	17

6.3 Pressure Time Product as a Function of Solids

From the previous discussion it is apparent that both system operating time and system pressure affect whey solids concentration in hyperfiltration. An attempt was made to establish a correlation. This is shown in Figure 23. For this particular analysis each individual solids concentration was used rather than averaged concentrations. This resulted in 118 data points giving a correlation for the range: $0 \leq Pt \leq 40000$

$$C = 6.2\, e^{36.9 \times 10^{-6} Pt} \qquad (18)$$

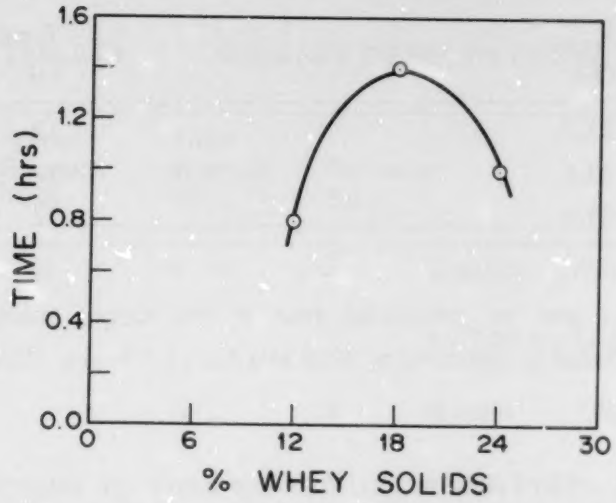


FIGURE 21 OPERATOR TIME SAVED BY ATTAINING A SPECIFIED SOLIDS CONCENTRATION AT 3700 kPa INSTEAD OF 3000 kPa

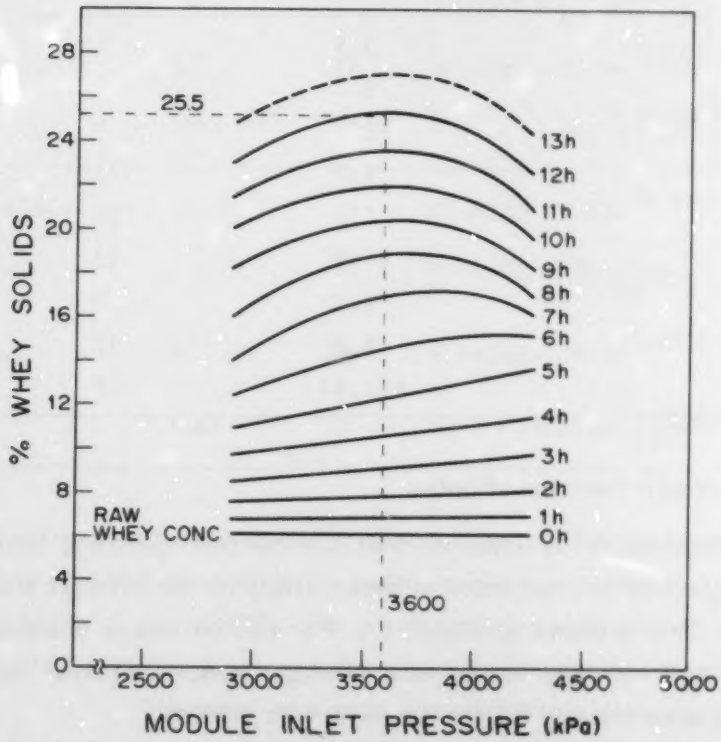


FIGURE 22 WHEY SOLIDS AS A FUNCTION OF MODULE INLET PRESSURE

where: C = concentrate whey solids (%)
P = system pressure (kPa)
t = time of run (hours)

The regression coefficient was calculated to be 0.987 with a standard error of the estimate (S.E.) equalling 1.53% solids. The 95% confidence interval for the function is shown in Figure 23 as ± 3%.

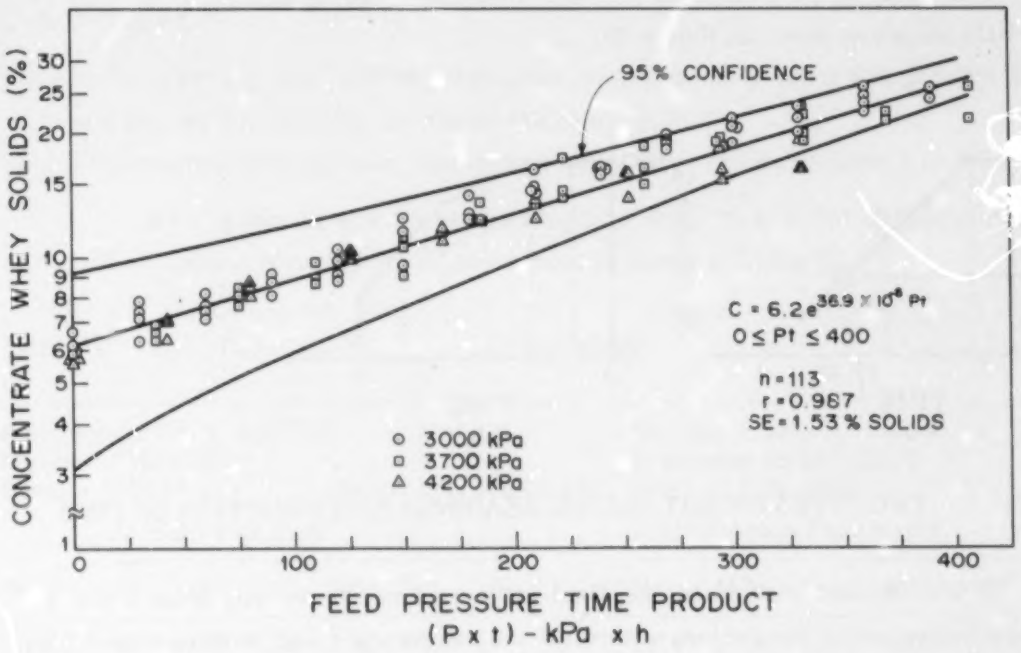


FIGURE 23 WHEY SOLIDS AS A FUNCTION OF THE FEED PRESSURE TIME PRODUCT

6.4 System Flux

System flux is an important property of any membrane separation technology since it is a measure of rate of volume throughput per unit of membrane area. The units are $L/m^2 \cdot h$. For hyperfiltration of whey, the permeate throughput is an important parameter. It is a measure of the rate of water removal from the raw whey and is calculated from the measured permeate flow rate and the total membrane area of each hyperfiltration module. In this study system flux determination became a real challenge.

It was unfortunate that the flow meters, which are of the rotameter type, were not calibrated during the testing program. According to the manufacturer's literature they could cover a flow range from 120 - 1 498 L/h.

Records concerning percent of full scale reading were kept. When the data were first analyzed in an attempt to correlate the flow meter reading to the actual flow in accordance with the calibration information noted above, a permeate volume equal to approximately three times the volume collected was calculated. Clearly, this was impossible, since all permeate was collected and the final volume was measured.

The data, when plotted as percent rotameter reading against time, had two characteristic shapes as shown in Figure 24.

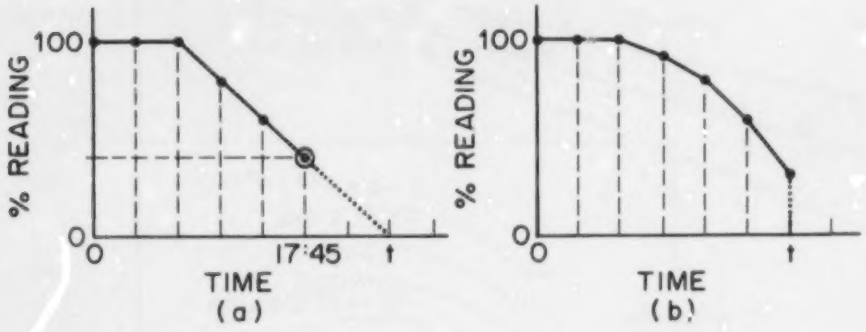


FIGURE 24 TWO TYPES OF ROTAMETER READINGS AS A FUNCTION OF TIME

It was decided that since the final volume of permeate was known, and the general flow behaviour of the permeate through the membrane could be determined from a plot of percent rotameter deflection against time, the instantaneous flux rates could be calculated. This was accomplished by the following procedure:

Case (a) Figure 24.

1) Calculate the total area under the curve.
2) If the last reading entered in the operations log was at, say, 17:45 and no further values prior to system shut-down were taken, then the previous three data points were plotted, linearly regressed and the time for zero percent reading calculated. This then gave a complete picture for flow readings against time and enabled calculation of the total area.

3) The total area under the curve is equal to the total permeate volume.

4) By calculating the area under the curve for each hour as a percentage of the total area, this could be correlated to the percent permeate of the total collected during that time.

5) Knowing the module membrane area enabled the calculation of the instantaneous flux.

6) This procedure was followed for all readings for all modules where the available flow data looked like that shown in Figure 24 (a).

Case (b) Figure 24.

1) In this case the last reading taken prior to system shut-down was greater than zero, and the total area under the curve was calculated.

2) The instantaneous flux calculation was made as described in steps 3 to 6 for case (a).

A computer program was written, data entered, and flux determinations made as described above. A sample computer output is shown in Table 23.

TABLE 23 TYPICAL FLUX CALCULATIONS

Day/Month/Year: 16/7/80 Run day = 394
Meter = 30476300 Shut down (H:M)--22:20
Press = 3500 kPa Permv = 27206 litres Sysrt = 12.50 hours

	Module Readings						Instantaneous Flux Rates					
Time	M1	M2	M3	M4	M5	M6	M1	M2	M3	M4	M5	M6
9:30	100	100	100	100	100	100	18.0	18.0	18.0	18.0	18.0	18.0
10:30	100	100	100	90	100	88	18.0	18.0	18.0	16.2	18.0	15.8
11:34	100	100	100	87	95	85	18.0	18.0	18.0	15.6	17.1	15.3
12:25	100	100	100	86	95	84	18.0	18.0	18.0	15.5	17.1	15.1
13:25	100	100	100	92	100	89	18.0	18.0	18.0	16.5	18.0	16.0
14:25	100	100	100	88	99	87	18.0	18.0	18.0	15.8	17.8	15.6
15:30	97	95	97	81	90	80	17.4	17.1	17.4	14.6	16.2	14.4
16:30	85	83	85	69	73	67	15.3	14.9	15.3	12.4	13.1	12.0
17:30	69	68	69	53	53	51	12.4	12.2	12.4	9.5	9.5	9.2
22:00	23	23	22	13	14	13	4.1	4.1	4.0	2.3	2.5	2.3
Individual module average flux rate =							**14.0**	**13.9**	**14.0**	**11.8**	**12.6**	**11.5**
System average flux rate =							**13.0**					

In this example the data for the 394th demonstration day is shown. The system was operational for a total of 12.5 hours. The collected permeate volume during that period amounted to 27 206 litres. Flow meter readings and their corresponding instantaneous flux are tabulated. Instantaneous flux varied from a high of 18 $L/m^2 \cdot h$ at the beginning of the run to 2.3 $L/m^2 \cdot h$ at the end, the decrease in flux being a function of the increase in feed solids concentration. For each of the modules an average flux was calculated, which in this example varied from 11.5 to 14 $L/m^2 \cdot h$. Differences in average flux between modules is indicative of membrane fouling. The final calculation was the system average flux which for this day was 13.0 $L/m^2 \cdot h$.

Analysis of the available data showed that the average system flux was not normally distributed (Figure 25). Two distinct distributions are indicated. The data for the second leg of the distribution are suspect. When examining the detailed data log it would appear that either the permeate volume is in error or the true length of the run was incorrectly recorded. In spite of these apparent difficulties one can use either of two approaches to the flux data analysis:

1) Draw two distributions and note the mean system flux value which in this case is 11.8 $L/m^2 \cdot h$, or,
2) take all 187 observations, calculate a mean and standard deviation. By following this approach the mean system flux is 12.1 $L/m^2 \cdot h$ with a standard deviation of 2.6 $L/m^2 \cdot h$.

Indeed, considering the underlying assumptions and potential errors, there is little to choose between the two mean system flux values. Based on familiarity with the data it is judged that average system flux values greater than 14 $L/m^2 \cdot h$ are due to data anomalies. Less than 20% of the data fall into this category.

Although the hyperfiltration system was batch operated and underwent a rigorous cleaning at the end of each day, the flux data were examined for deterioration in system flux over time. For instance, since the plant was operating on a five-day week with disinfectant circulating over the weekend (two days) one would expect that the average system flux rates for Mondays would be higher than for Fridays. Table 24 summarizes these data.

The average system flux for each of the days of the week were not normally distributed. Again two distinct distributions were evident. The data in Table 24 show the mathematically derived statistics and the statistics based on a curve fitting by eye.

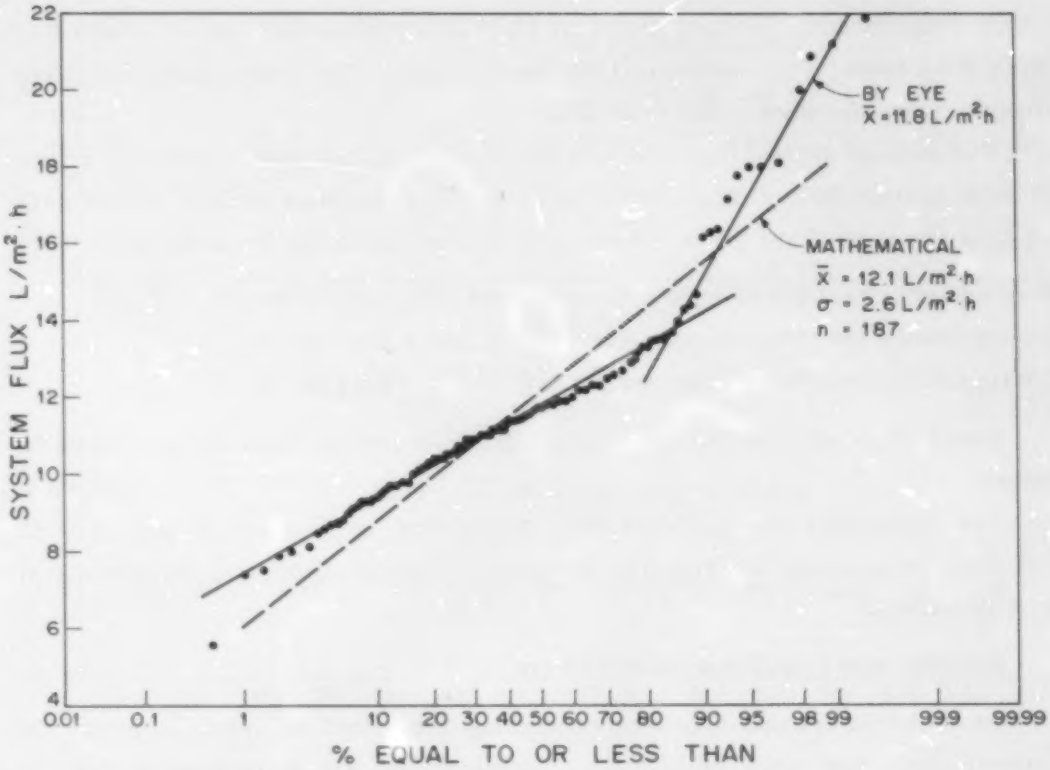


FIGURE 25 SYSTEM FLUX DISTRIBUTION

TABLE 24 AVERAGE SYSTEM FLUX ACCORDING TO DAYS OF THE WEEK

		Mathematical Determination		By eye	
Day of Week	n	$\bar{x}$	σ	$\bar{x}$	σ
Monday	46	12.6	2.7	12.0	1.7
Tuesday	46	12.2	2.5	11.8	1.7
Wednesday	48	11.9	2.6	11.5	1.7
Thursday	31	11.6	2.0	11.4	1.6
Friday	18	11.6	3.0	11.6	2.4

Only the difference in the standard deviation between the two approaches to data analysis is significant. The data show that there is a gradual decrease in system flux as the week progresses. This confirms earlier expectations. The deterioration in system flux with time during the week is less than 10%.

The average system flux data was also plotted against time as shown in Figure 26. The mean system flux of 12.1 $L/m^2 \cdot h$ and the 95% confidence interval for all data excluding days 399 and 420 are shown. From the data analyses it can be stated with:

1) 95% confidence that the average system flux is 12.1 $\pm$ 5.1 $L/m^2 \cdot h$;
2) 68% confidence that the average system flux is 12.1 $\pm$ 2.6 $L/m^2 \cdot h$;
3) 50% confidence that the average system flux is 12.1 $\pm$ 1.8 $L/m^2 \cdot h$.

Based on a coefficient of variation of 21%, the system flux data are judged to be consistent.

The hyperfiltration manufacturers stated that an average system flux of 12 $L/m^2 \cdot h$ could be obtained for the whey permeate. The data from this demonstration run support this claim.

6.5 Instantaneous Flux/Total Solids Effects

As noted in Section 6.2, data concerning the effect of system pressure on solids concentration rate were collected. Calculation of the instantaneous flux as discussed in Section 6.4 allowed for the combination of this data with the solids data.

Figure 27 shows the correlation of instantaneous flux with percent solids for a system pressure of 3000 kPa for experiment days 574-578. From these data at 3000 kPa pressure, the following conclusions are drawn:

1) As the whey feed solids concentration increases, the instantaneous system flux decreases linearly in accordance with the equation:

$$F_{30} = 28.6 - 1.34 \text{ (\% solids)} \qquad (19)$$

where: F_{30} = instantaneous sytem flux at 3000 kPa pressure ($L/m^2 \cdot h$).

2) The correlation is valid over the range of $5 \leq$ % solids ≤ 21.3.
3) Based on 28 observations the correlation coefficient is 0.977.
4) The standard error of estimate (SE) equals 1.41 $L/m^2 \cdot h$. This means that for the data to be normally distributed, 68% of the values should lie within the band of $\pm$ 1.41 $L/m^2 \cdot h$.

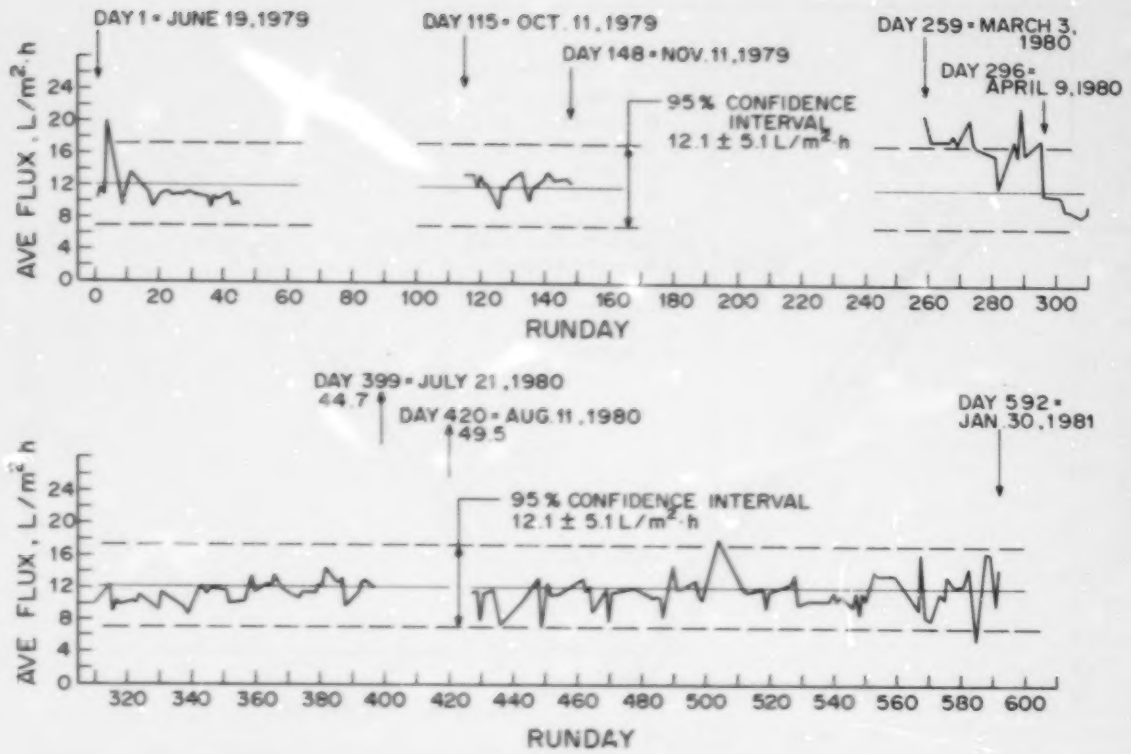


FIGURE 26 AVERAGE SYSTEM FLUX AS A FUNCTION OF TIME

5) The maximum solids concentration which can be attained at 3000 kPa is:

$21.3 \pm 1.1\%$

6) The maximum instantaneous flux at zero % solids is 28.6 $L/m^2 \cdot h$.

A similar correlation between instantaneous system flux and percent solids exists for a system pressure of 3 700 kPa (Figure 28). Three days of solids and flux data were available (days 581-583). The following conclusions are drawn:

1) As the whey feed solids concentration increases, the instantaneous system flux decreases linearly in accordance with the equation:

$$F_{37} = 29.5 - 1.32 \text{ (\% solids)} \qquad (20)$$

where: F_{37} = instantaneous system flux at 3 700 kPa pressure ($L/m^2 \cdot h$).

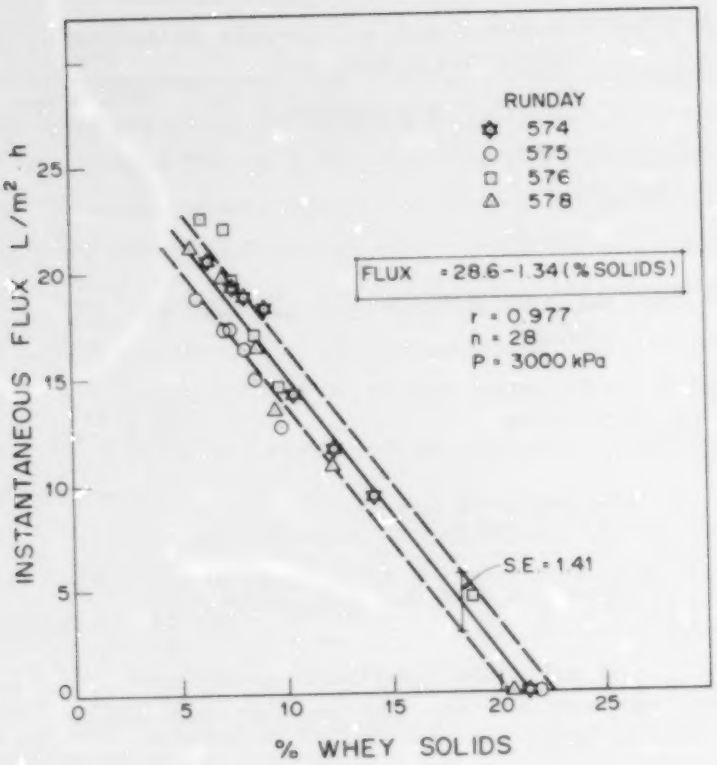


FIGURE 27 INSTANTANEOUS FLUX CHARACTERISTICS AS A FUNCTION OF WHEY SOLIDS AT 3000 kPa

2) The correlation is valid over the range $5 \leq$ % solids ≤ 22.3.

3) The correlation coefficient based on 17 observations is 0.980.

4) The standard error of estimate (SE) equals 1.41 $L/m^2 \cdot h$. For the data to be normally distributed, 68% of the values should lie within $\pm$ 1.41 $L/m^2 \cdot h$ of the correlation.

5) The maximum attainable solids concentration at a system pressure of 3700 kPa is:

$22.3 \pm 1.1\%$

6) At zero % solids concentration the maximum instantaneous flux is 29.5 $L/m^2 \cdot h$.

For the case of 4200 kPa system pressure the data are similarly correlated as shown in Figure 29. Only 12 data points for experimental run days (588, 589 and 592) were available. From the data the following conclusions are drawn:

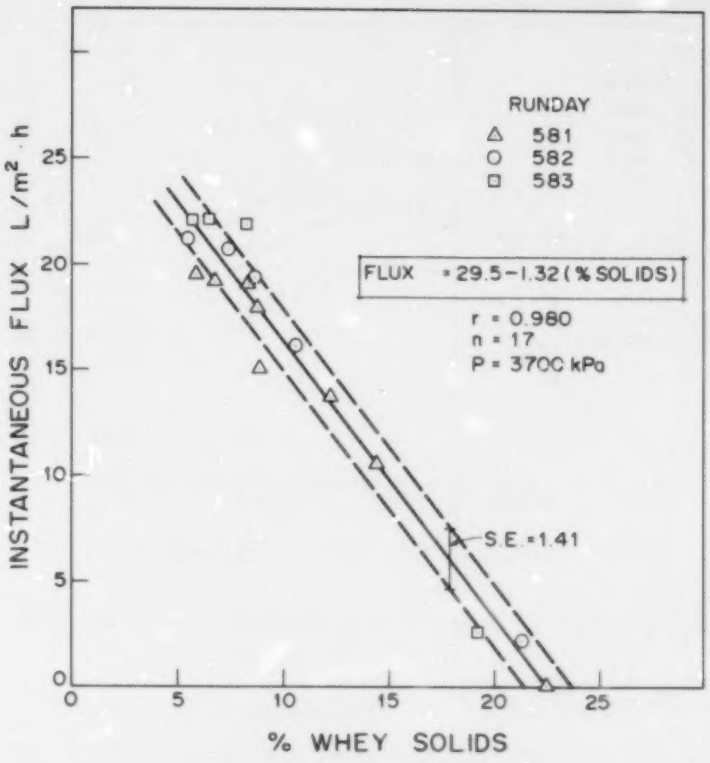


FIGURE 28 INSTANTANEOUS FLUX CHARACTERISTICS AS A FUNCTION OF WHEY SOLIDS AT 3700 kPa

1) A feed solids concentration increase results in a linear instantaneous system flux decrease which corresponds to the following equation:

$$F_{42} = 34.0 - 1.67 \text{ (\% solids)} \qquad (21)$$

where: F_{42} = instantaneous system flux at 4200 kPa pressure ($L/m^2 \cdot h$).

2) The correlation is valid over the range $5 \leq$ % solids ≤ 20.

3) The correlation coefficient based on 12 observations is 0.957.

4) The standard error of estimate (SE) equals 2.4 $L/m^2 \cdot h$. Even though only 12 data points exist, the data are normally distributed.

5) The maximum attainable solids concentration at a system pressure of 4200 kPa is:

$20.4 \pm 1.4\%$

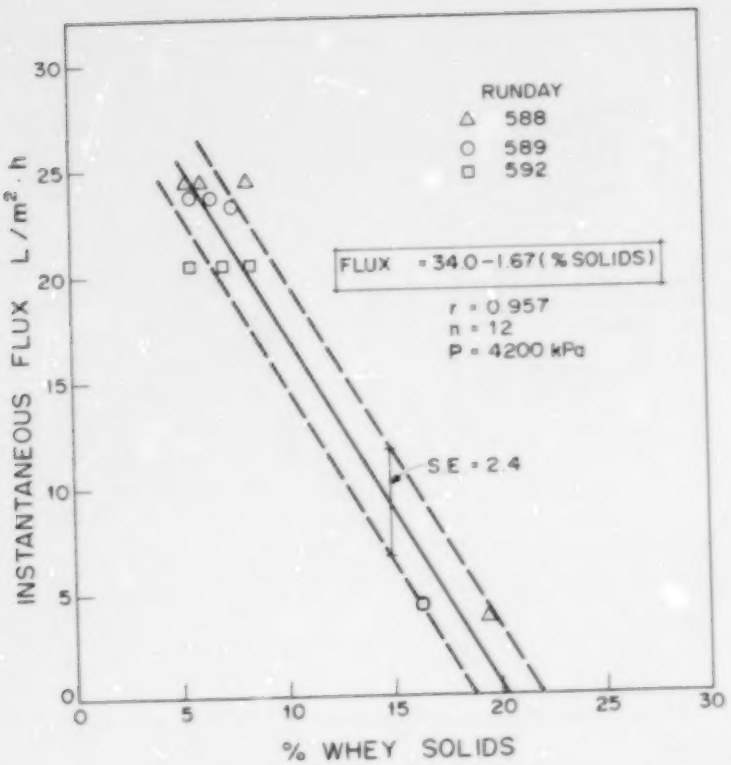


FIGURE 29 INSTANTANEOUS FLUX CHARACTERISTICS AS A FUNCTION OF WHEY SOLIDS AT 4200 kPa

6) A maximum instantaneous sytem flux of 34.0 $L/m^2 \cdot h$ occurs at zero solids concentration.

The information of interest as far as system operation is concerned is: what is the optimum pressure/solids relationship? To answer this question the data developed above can be plotted as shown in Figure 30. The data would indicate that at a system pressure of 3600 kPa a maximum solids concentration of 22.3 $\pm$ 1.1% can be attained, compared with 25.5% at 3600 kPa for a 12 hour run (Figure 22).

An attempt was also made to combine all data and present a correlation which would be valid for the pressure range $3000 \leq P \leq 4200$. This is shown in Figure 31. The following conclusions can be drawn:

1) The data correlate linearly in accordance with:

$$F = 30.1 - 1.41 \text{ (\% solids)} \qquad (22)$$

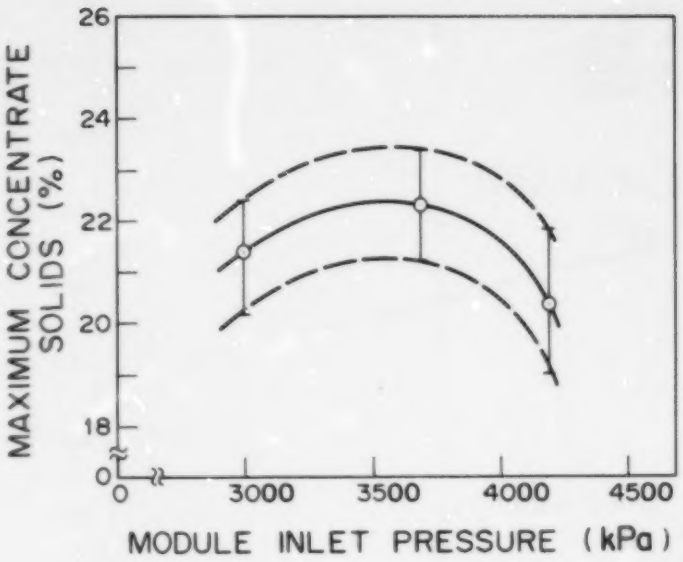


FIGURE 30 MAXIMUM ATTAINABLE CONCENTRATE SOLIDS

where: F = instantaneous system flux for $3000 \leq P \leq 4200$ kPa ($L/m^2 \cdot h$).

2) The correlation is valid over the range $5 \leq$ % solids ≤ 22.3.

3) Based on 57 observations the correlation coefficient is 0.960.

4) The standard error of estimate (SE) is 2.0 $L/m^2 \cdot h$. The data are normally distributed.

5) The above equation for predicting the maximum solids concentration for the whey concentrate (for $3000 \leq P \leq 4200$) shows that the maximum attainable solids concentration is $21.3 \pm 1.5\%$.

Aside from the foregoing discussions focussing on solids characteristics of the whey concentrate, whey permeate characteristics are also important. They not only indicate whether or not permeate treatment is required but also enable one to assess certain membrane rejection characteristics.

6.6 Permeate

Data concerning certain production ratios were calculated from the records kept during the demonstration run. The permeate mass to milk mass ratio data as shown in Figure 32 indicate a normal distribution of highly reliable data (CV = 7.1%). The mean permeate mass to milk mass ratio is 0.62 with a standard deviation of 0.04. This means

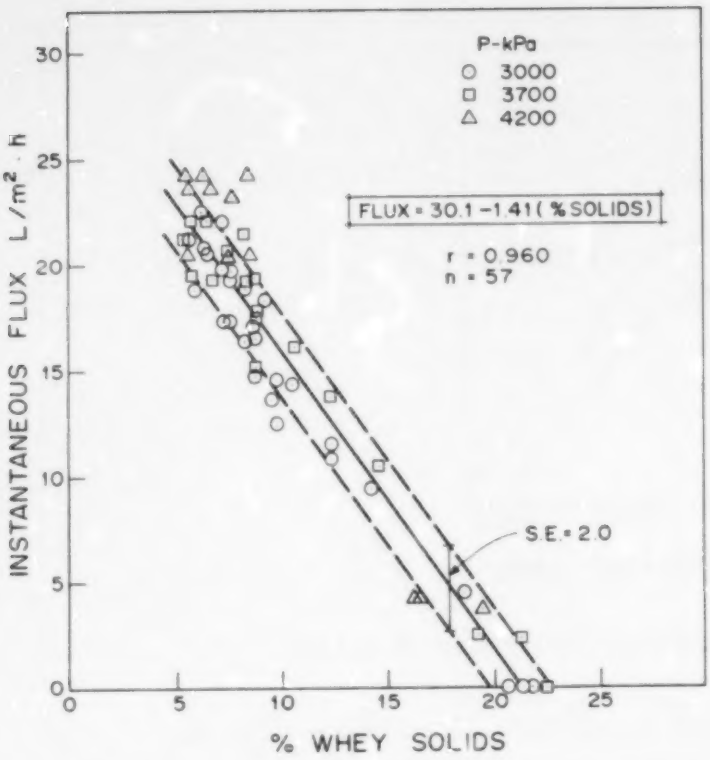


FIGURE 31 INSTANTANEOUS FLUX CHARACTERISTICS AS A FUNCTION OF WHEY SOLIDS

that it can be stated with 95% confidence that, for every 1 kg of milk, between 0.54 to 0.70 kg of permeate will result.

Similarly, the permeate to raw whey data are shown in Figure 33. The distribution is normal and the data are highly reliable (CV = 6.7%). In only 5 out of 100 observations would we expect to need more or less than 1.3 -1.7 kg of raw whey to obtain 1 kg of permeate.

The permeate mass to concentrate mass ratios were plotted in a similar manner. The data were found to be not quite normally distributed. The coefficient of variation though was 23%, indicating that the data were fairly consistent. Mathematically the mean ratio is 2.29 with a standard deviation of 0.53. This means in 95 out of 100 times, between 1.3 to 3.3 kg of permeate will be obtained for every 1 kg of concentrate. These data are summarized in Table 25. The design permeate to concentrate ratio claimed by the manufacturer is 3.0.

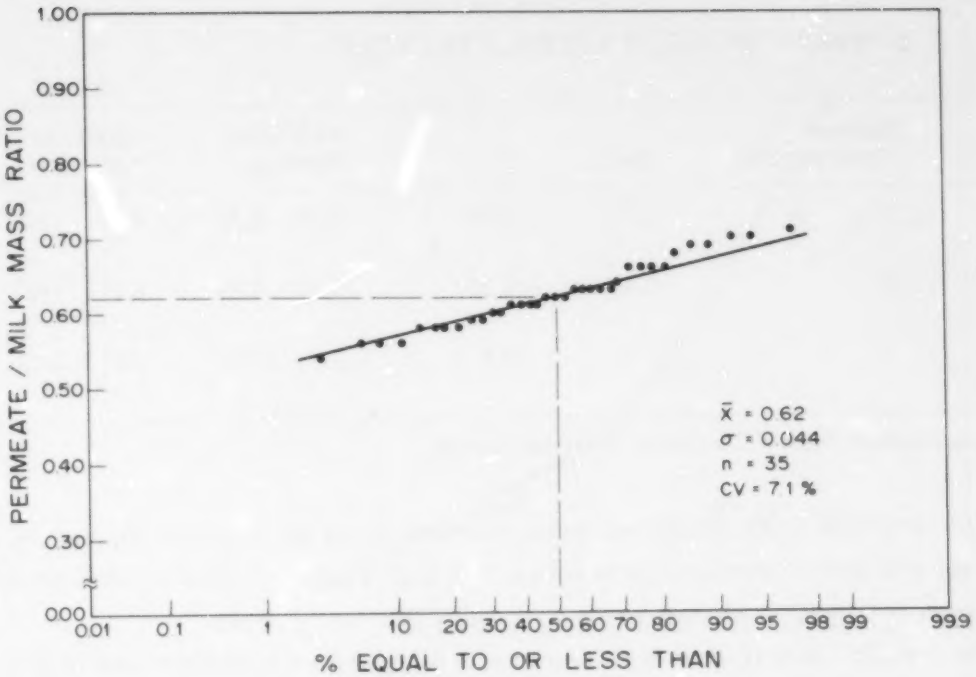


FIGURE 32 PERMEATE TO MILK MASS RATIO DISTRIBUTION

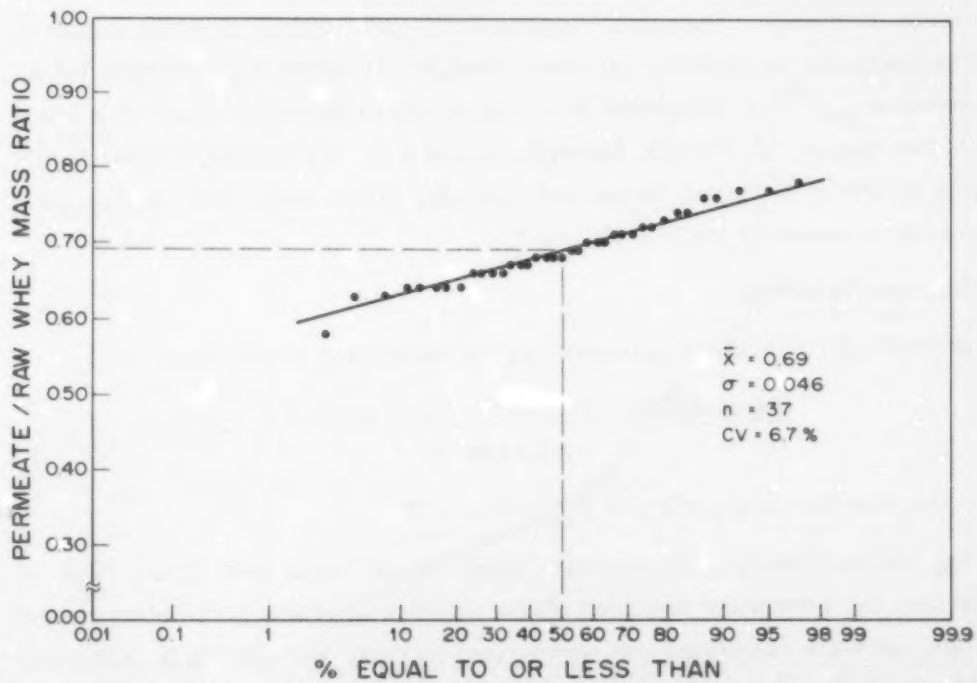


FIGURE 33 PERMEATE TO RAW WHEY MASS DISTRIBUTION

TABLE 25 SUMMARY OF VARIOUS PERMEATE RATIOS

Parameter	Number of Observations	Ratio	σ	95% Conf. Interval	Coeff. of Variation	
Permeate/ Milk	35	0.62	0.04	0.54 - 0.70	7.1	HC
Permeate/ Raw Whey	37	0.69	0.05	0.59 - 0.79	6.7	HC
Permeate/ Concentrate	35	2.3	0.5	1.3 - 3.3	23	FC

HC = highly consistent data; FC = fairly consistent data.

The permeate COD, BOD_5 and solids characteristics are shown in Figures 34, 35 and 36. Not one of the distributions is normal. A high degree of data variability is indicated. However, a number of statements concerning this can be made.

For the COD data (Figure 34) it can be said that, while the median value is 850 mg/L, concentrations as high as 2 700 mg/L can occur. The BOD_5 data (Figure 35) is considerably more variable. A median value might be 430 mg/L. Concentrations of 1 000 mg/L are not uncommon. Data excursions to 2 500 and 3 500 mg/L would appear to be suspect. It is interesting to observe that the COD/BOD_5 ratio for the permeate for all practical purposes is 2. This compares to a raw whey COD/BOD_5 ratio of 2.3 and indicates that the degree of product biodegradability has not changed appreciably. Permeate solids as shown in Figure 36 are not normally distributed. The median total solids concentration as drawn by eye is 1 500 mg/L.

6.7 Membrane Rejection

The rejection of various constituents by the membrane is calculated by

$$R = \frac{\text{Parameter In - Parameter Out (Permeate)}}{\text{Parameter In}} \times 100$$

where: R = the rejection of a particular parameter in %.

Using the raw whey and permeate total solids, COD and BOD_5 data as summarized earlier, the membrane rejection characteristics for these parameters can be calculated. These data are calculated and summarized in Table 26. For COD, BOD_5 and total solids the rejection is approximately 98%.

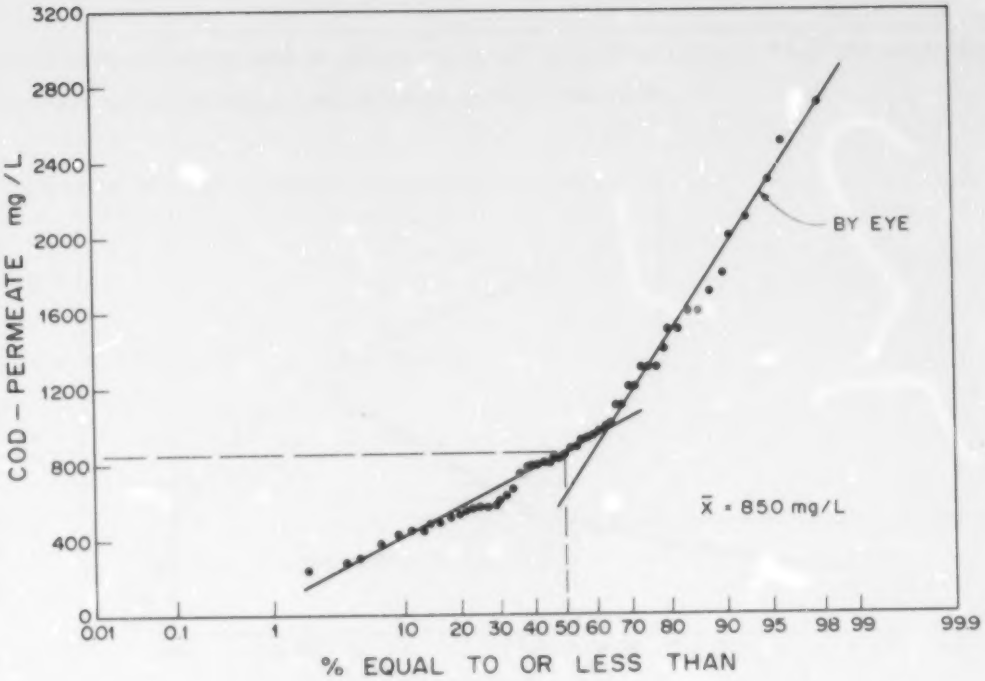


FIGURE 34 PERMEATE COD DISTRIBUTION

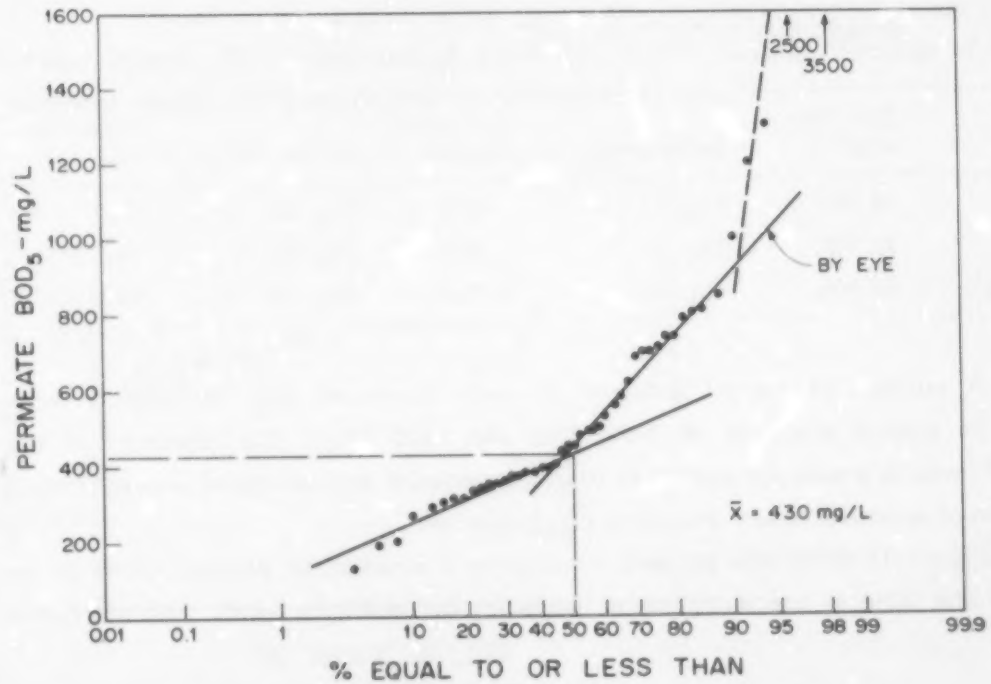


FIGURE 35 PERMEATE BOD_5 DISTRIBUTION

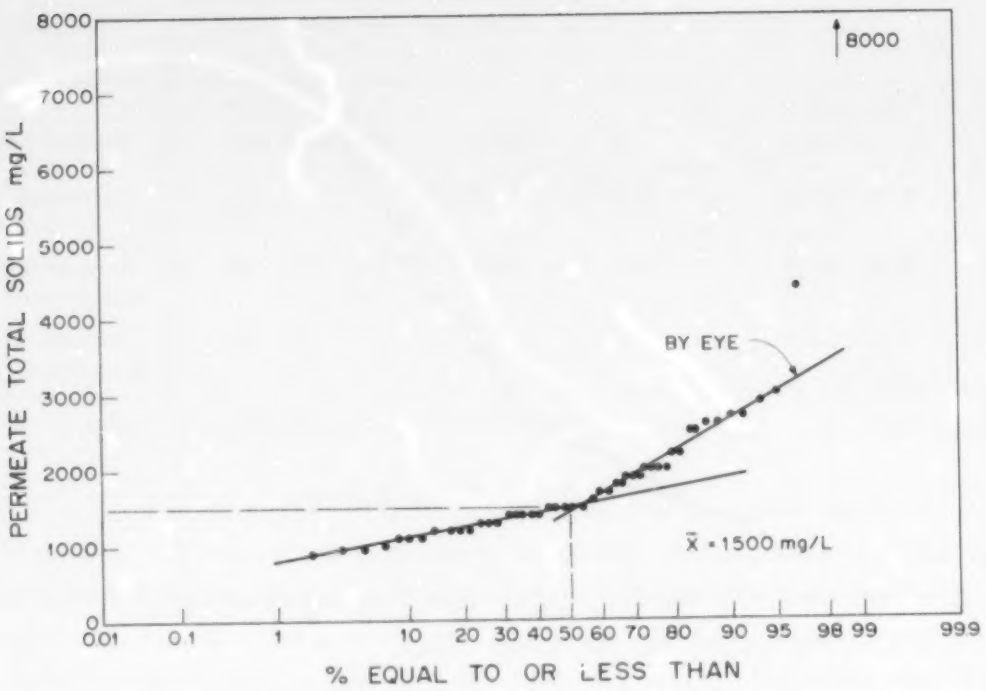


FIGURE 36 PERMEATE TOTAL SOLIDS DISTRIBUTION

TABLE 26 MEMBRANE REJECTION DATA

Parameter	Raw Whey (mg/L)	Reference	Permeate (mg/L)	Reference	Rejection (%)
COD	64 000	Fig. 15	850	Fig. 34	98.7
BOD_5	29 500	Fig. 17	430	Fig. 35	98.5
Total solids	62 400	Fig. 4	1 500	Fig. 36	97.6

A number of special analyses on both permeate and concentrate were conducted at system pressures of 3000, 3700 and 4200 kPa. The objective of this investigation was to assess the change in whey concentrate and permeate characteristics as a function of system pressure and solids concentration.

Figure 37 shows the percent minerals as a function of percent solids in the permeate. The mineral concentration in the whey permeate increases with increasing

solids concentration and is independent of system pressure. This demonstrates that the minerals in the permeate are associated with the solids.

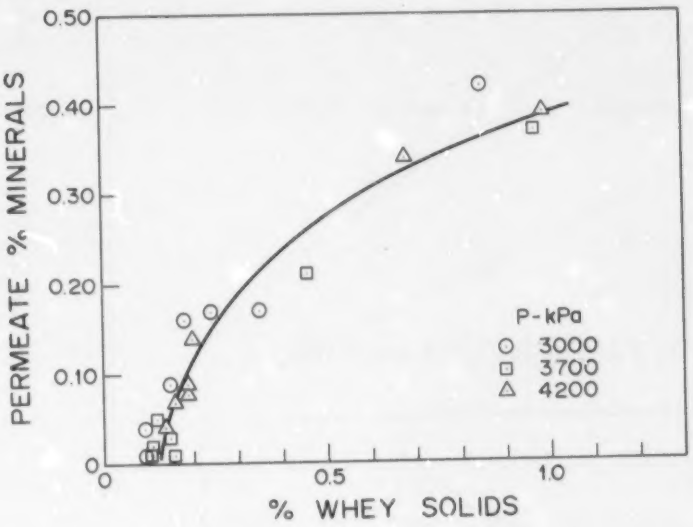


FIGURE 37 MINERALS IN PERMEATE

Protein concentration in the permeate is independent of solids and system pressure (Figure 38). Protein leakage is constant a 0.3% protein. Because of their large molecular weight, proteins are retained in the concentrate.

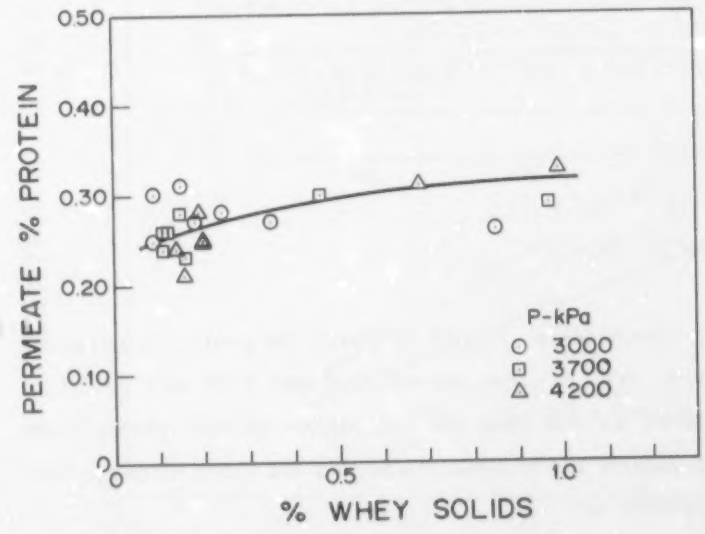


FIGURE 38 PROTEIN IN PERMEATE

The rejection of the concentrate whey constituent minerals, protein and fat is illustrated in Figures 39, 40, and 41. As noted earlier the minerals are associated with the solids. The data in Figure 39 confirm this. increasing solids concentration brings about a corresponding increase in minerals, independent of system pressure. This behaviour can be described by the equation:

$$\% \text{ Minerals in Concentrate} = 0.075\ (\% \text{ solids}) - 0.051 \qquad (24)$$

$r = 0.985$

$n = 21$

$3000 \leq P \leq 4200$

P = system pressure in kPa

Twenty-four percent whey concentrate will contain 1.75% minerals.

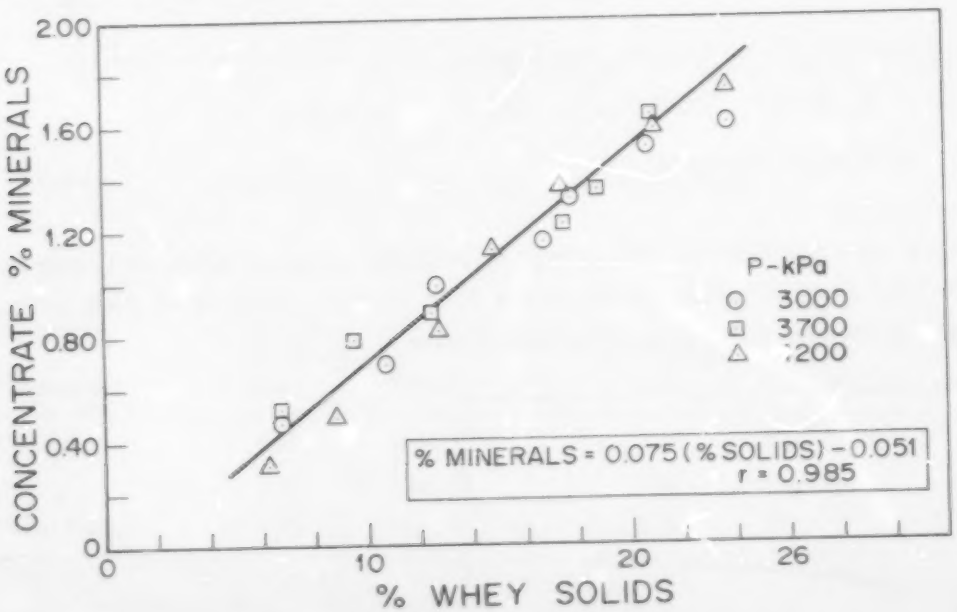


FIGURE 39 MINERALS IN CONCENTRATE

Protein is retained in the concentrate. Figure 40 shows the protein concentration as a function of solids. The lower system pressures of 3000 and 3700 kPa result in lower protein concentrations compared to the case of the higher system pressure of 4200 kPa, possibly because, at high pressure, the protein molecules are more strongly tied up with the solids. The data are correlated as:

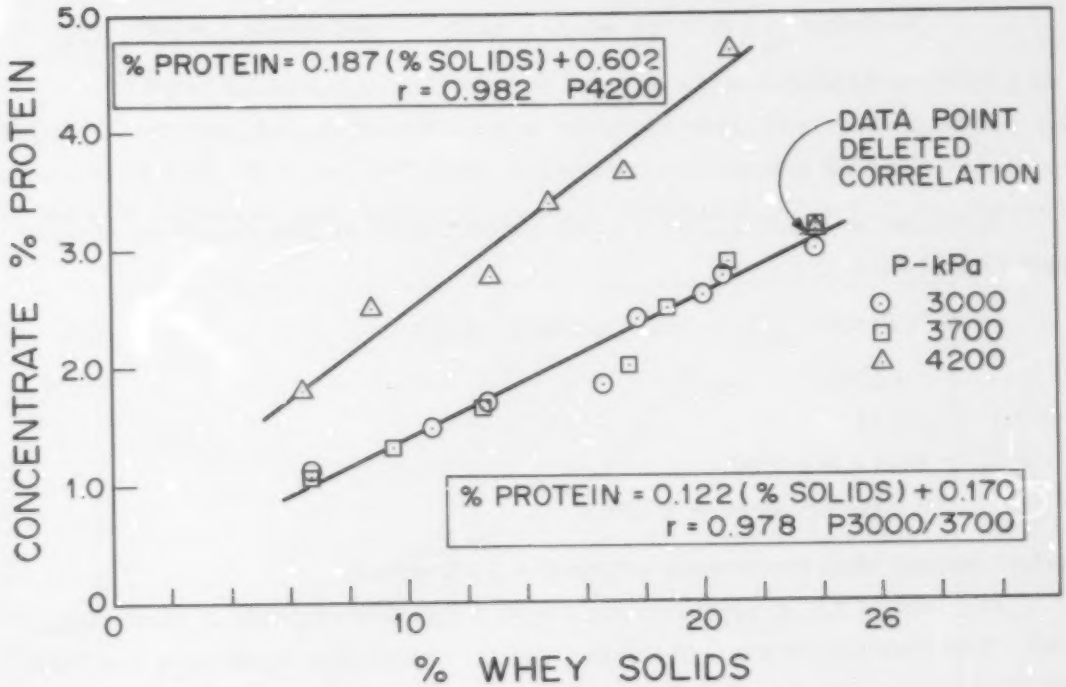


FIGURE 40 PROTEIN IN CONCENTRATE

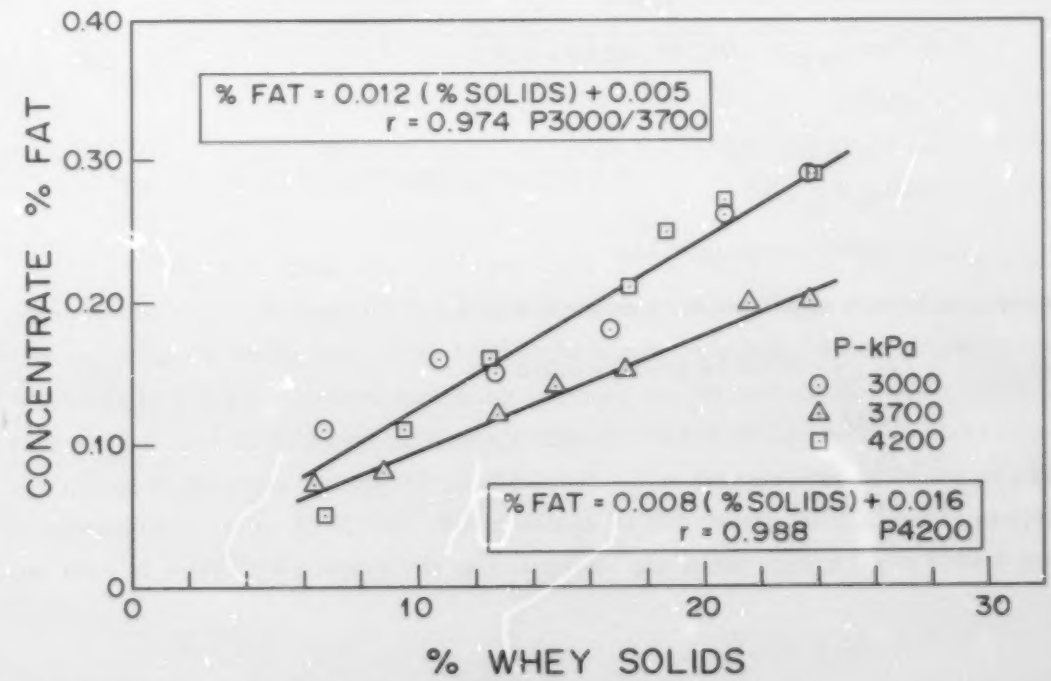


FIGURE 41 FAT IN CONCENTRATE

$$\% \text{ Protein}_{42} = 0.187\ (\% \text{ solids}) + 0.602 \quad (25)$$

$r = 0.982$

$n = 6$

$P = 4200$ kPa

It should be recalled that a solids concentration of 24% cannot be attained when operating at 4 200 kPa.

$$\% \text{ Protein}_{30/37} = 0.122\ (\% \text{ solids}) + 0.170 \quad (26)$$

$r = 0.978$

$n = 14$

$3000 \leq P \leq 3700$

P = system pressure in kPa

Twenty-four percent whey concentrate will contain 3.1% protein.

The fate of fat in whey concentrate as a function of solids is illustrated in Figure 41. Two functions describe the data. The fat retention is higher at a low (3000 and 3700 kPa) system pressure. At high system pressure (4200 kPa) it would appear that some fat molecules are forced through the membrane. Unfortunately, fat analyses for the permeate were not conducted. An increase in fat concentration in the permeate would have removed any speculation in this regard.

$$\% \text{ Fat}_{30/37} = 0.012\ (\% \text{ solids}) + 0.005 \quad (27)$$

$r = 0.974$

$n = 7$

$3000 \leq P \leq 3700$

P = system pressure in kPa

At 24% whey concentrate solids the fat content is 0.29%.

$$\% \text{ Fat}_{42} = 0.008\ (\% \text{ solids}) + 0.016 \quad (28)$$

$r = 0.988$

$n = 14$

$P = 4200$ kPa

6.8 Water Consumption

Water consumption records were kept and water useage recorded on a routine basis. In addition, hourly records were kept for 12 days, four at each of the system pressures of 3000, 3700 and 4200 kPa. The objective of varying the system pressure was to see if it influenced total water consumption. Figures 42, 43 and 44 summarize these data.

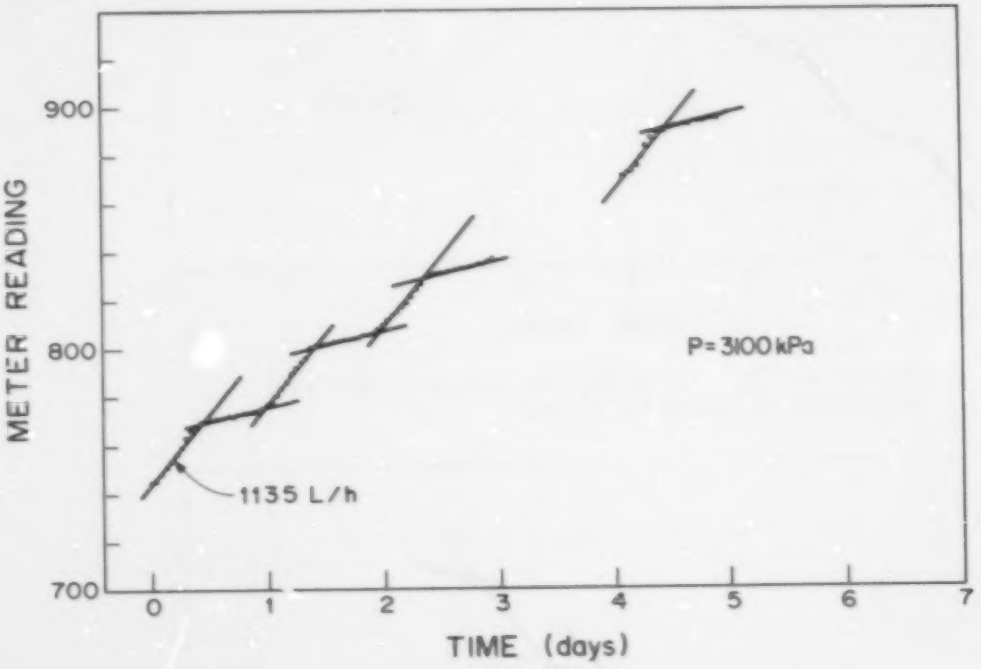


FIGURE 42 PLANT WATER CONSUMPTION RATE AT 3100 kPa HYPERFILTRATION PRESSURE

The data show that for the first 10 hours, starting at 0745 h, the water consumption rate averages 1 135 L/h irrespective of system operating pressure. During the following 14 hours, i.e., after 1745 h the water consumption rate drops to anywhere from 200 to 415 L/h. System operating pressure has no influence. Using the 1 135 L/h rate for the first 10 hours and an average rate of 300 L/h for the next 14 hours results in a calculated daily water useage of 15 500 litres. The average daily amount of raw whey processed amounts to 35 700 kg. Water useage at the cheese plant amounts to 0.43 litres per litre of whey. This represents an extremely low water useage for a cheese plant and

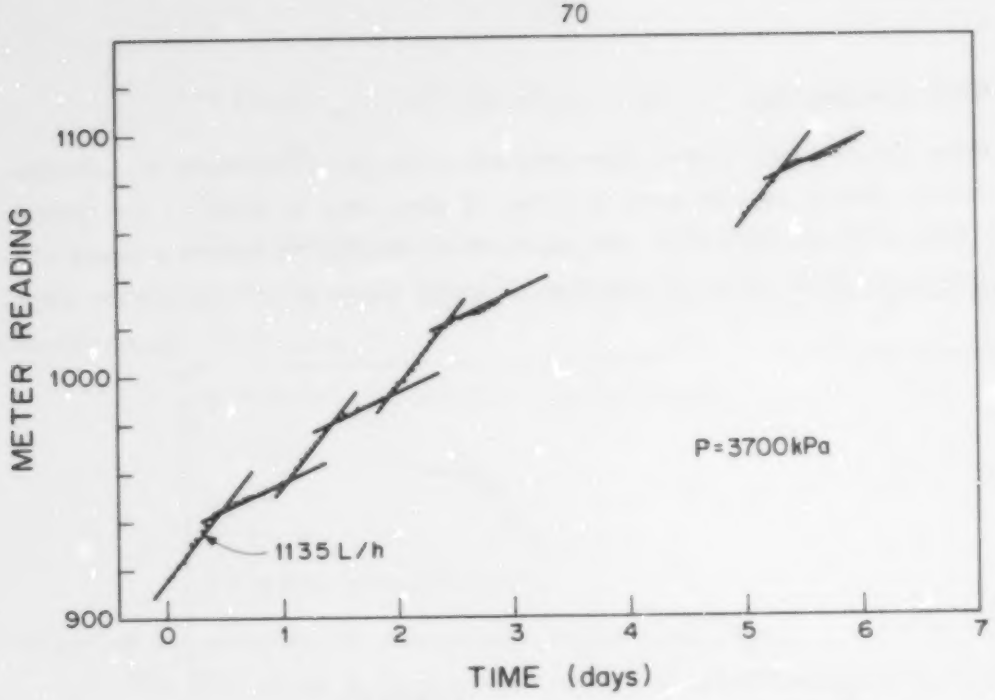


FIGURE 43 PLANT WATER CONSUMPTION RATE AT 3700 kPa HYPERFILTRATION PRESSURE

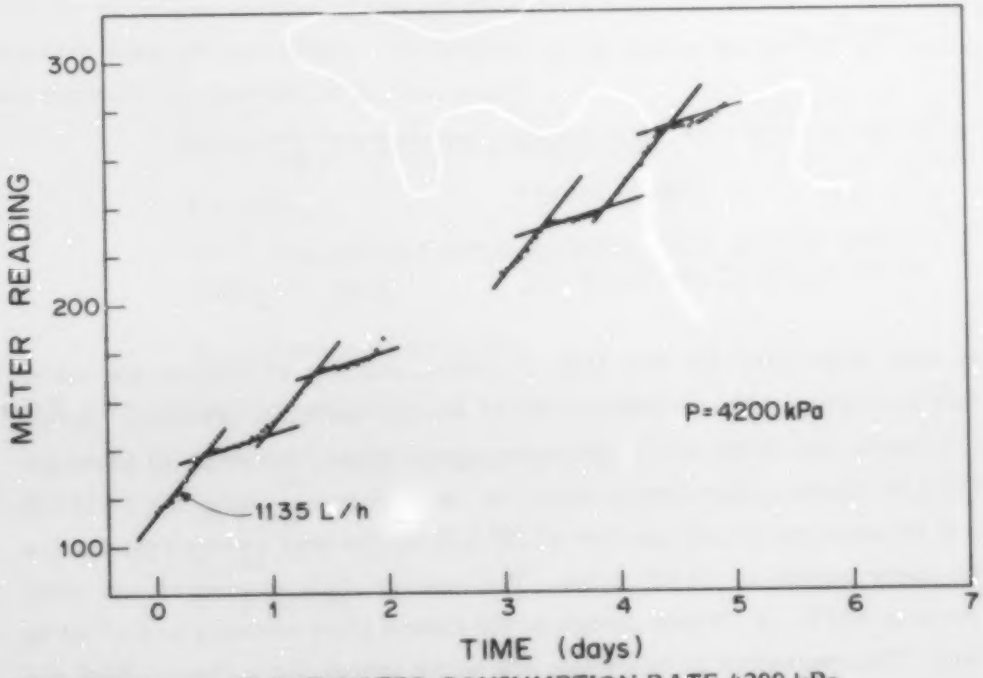


FIGURE 44 PLANT WATER CONSUMPTION RATE 4200 kPa HYPERFILTRATION PRESSURE

is commendable. The water use target for cheese plants is 1 litre of water per litre of whey processed (8).

Similarly the raw water to milk processed ratio is calculated as 0.40. This means that for every 5 litres of milk processed 2 litres of water are required.

7 PROCESS ECONOMICS

In the previous sections the various technical aspects of the hyperfiltration process and its long-term performance at La Fromagerie d'Oka have been described in some detail. From the observations it is concluded that the hyperfiltration of raw whey from approximately 6% total solids to approximately 24% total solids was extremely successful. The remaining question to be answered concerns the cost of concentrating 6% whey to 24%.

Table 27 summarizes the various cost components based on 1979 dollars. The total annual cost is calculated to be $184 800. On a percentage basis this is distributed between maintenance, operation and capital as follows:

Maintenance	19%
Operation	36%
Capital	45%

Based on 250 operating days per year, the daily cost of solids concentration would be 739 dollars. This can be converted to a cost per kg of solids recovered as follows:

daily whey @ 6.24% = 35 700 kg
daily solids recovery (efficiency = 97.6%) = 2 175 kg
daily system cost = $739

$$\frac{\$739/\text{day}}{2\,175\ \text{kg/day}} = 34¢ \text{ per kg}$$

∴ Cost to produce food grade whey concentrate at approximately 24% solids is 34¢ per kg.

A recent article (11) provided information on cost index trends since the early fifties. The cost indexes were only increasing by approximately 3% per year from 1950 to 1970. Since 1970 the cost indexes have increased by an average of 9 to 10% per year. In light of this, the 1983 cost (C_{1983}) to produce food grade whey concentrate of approximately 24% solids has been adjusted to reflect a 9% per annum cost increase, and is calculated to be:

$$C_{1983} = \frac{[\$83\,500\,(1.09)^4 + (\$66\,262 + \$35\,040)(1.09)^3]100}{250 \times 2\,175} = 46¢ \text{ per kg}$$

TABLE 27 HYPERFILTRATION COST SUMMARY

Item		Units	Rate	Sub-Cost	Annual Cost
A. Capital Cost					
1.0	Equipment				
1.1	6 hyperfiltration modules including all accessories	1979 Cdn $	-	164 000	
1.2	Spare parts	1979 Cdn $	-	4 500	
2.0	Ancillary Equipment				
2.1	Refitting of pasteurizer	1979 Cdn $	-	9 500	
2.2	Chilling plates	1979 Cdn $	-	5 500	
2.3	Ice bank and compressors	1979 Cdn $	-	29 000	
2.4	Holding tanks (7)	1979 Cdn $	-	15 000	
2.5	Miscellaneous pumps	1979 Cdn $	-	2 500	
2.6	Separator (used)	1979 Cdn $	-	8 500	
3.0	Laboratory Equip.			5 500	
4.0	Installation including all mech. electrical, struc., modifications and start-up	1979 Cdn $		90 000	
	TOTAL	1979 Cdn $		334 000	
Depreciation		1979 Cdn $	10% per year		33 400
Interest		1979 Cdn $	15% per year		50 100
TOTAL CAPITAL COST		1979 Cdn $	-	--	**83 500**
B. Operations Cost					
1.0	Labor	1.5 men x 42.5 h/wk x 52 wks	$7.50 per h	--	24 860
2.0	Cleaning Supplies	12 months	$950 per month	--	11 400
3.0	Energy Costs	12 months	$2 500 per month	--	30 000
TOTAL OPERATIONS COST		1979 Cdn $	-	--	**66 260**
C. Maintenance Cost					
1.0	General Maintenance				20 000
2.0	Membrane Replacement	280 x 6 = 1 680 membranes	over 5 yrs. $15/membrane assembly	$\frac{1\,680 \times 15}{5}$	5 040
3.0	Miscellaneous - laboratory - supervision - administration				10 000
TOTAL MAINTENANCE COST					**35 040**
TOTAL SYSTEM COST*		1979 Cdn $			**184 800**

* Building costs excluded.

If no whey recovery is practiced, the pollution potential from a cheese manufacturer such as La Fromagerie d'Oka is 14 200 population equivalent. Whey recovery reduces this to a pollution load of 450 p.e. Using activated sludge as one example of waste treatment technology, costs have been estimated as summarized in Table 28.

The example in Table 28 shows that a net savings of 108 cents per kg [168 - (14 + 46)] of whey solids could be realized if hyperfiltration is used as a solids concentration recovery technology and the total effluent (permeate + process water) is treated using activated sludge treatment technology. Application of alternative treatment technologies must be evaluated on a case-by-case basis.

An investment in capital equipment is usually made with the expectation of reducing overall costs. The time required to repay the original investment from cost savings generated by this capital equipment acquisition is known as the payback period. A number of approaches to calculate this payback period are available. Recently, a payback formula which takes inflation into consideration has been proposed (12). Simply stated it says that, when the future values of the present investment plus the annual maintenance and operation costs equal the savings, then the payback period coincides.

Mathematically, this is expressed as:

$$F_1 + F_2 = F_3 \tag{29}$$

where: F_1 = future value of the present investment

F_2 = future value of the uniform stream of annual maintenance and operation

F_3 = future value of the uniform stream of savings

and

$$F_1 = P(1 + i)^n \tag{30}$$

$$F_2 = A \frac{(1 + i)^n - (1 + e)^n}{(i - e)} \tag{31}$$

$$F_3 = S \frac{(1 + i)^n - (1 + r)^n}{(i - r)} \tag{32}$$

where: P = present investment

n = payback period

i = the cost of capital

TABLE 28 POTENTIAL COST IMPACT OF WHEY RECOVERY/TREATMENT (Hyperfiltration/Activated Sludge) ALTERNATIVES

	Estimated Costs (1983)								
	Pop. Equiv. (p.e.)	Dollars/Capita O&M	Dollars/Capita Capital	Annual O&M	Total Capital	Total Dollars Annual**	Treatment Cost cents/kg solids	Hyperfiltration Cost cents/kg solids	Minimum Total Cost cents/kg solids
No Recovery	14 200	9.95	224	141 300	3 180 000	936 300	168	--	168
Recovery	450	12.75	569	10 000*	160 000	75 000	14	46	60

* considered to be a minimum O&M cost
** 10% depreciation on capital, 15% interest rate

A = annual maintenance and operation cost in the 1st year

e = inflation rate for maintenance and operation costs

S = savings in the first year

r = annual inflation rate for the product

Therefore, according to the payback definition, "n" is the time where:

$$F_1 + F_2 = F_3$$

and

$$P(1+i)^n + A\,\frac{(1+i)^n - (1+e)^n}{(i-e)} = S\,\frac{(1+i)^n - (1+r)^n}{(i-r)} \qquad (33)$$

The solution to this equation is obtained by trial and error. For the case of La Fromagerie d'Oka, the payback period can be calculated as follows:

Installed cost of hyperfiltration system (P):	$471 500
First year operating and maintenance cost (A):	$131 200
First year cost savings (168-60)¢/kg x 2175 kg/d x 250 days) (S):	$587 250
Money interest rate (i):	13% (assumed)
Money inflation rate (e):	8% (assumed)
Savings inflation rate (r):	9% (assumed)

$$471\,500(1+0.13)^n + 131200\,\frac{(1+0.13)^n - (1+0.08)^n}{(0.13-0.08)} = 587\,250\,\frac{(1+0.13)^n - (1+0.09)^n}{(0.13-0.09)}$$

La Fromagerie d'Oka's payback period for the investment in the hyperfiltration system has been calculated at 14 months.

The payback period will be different for other interest and inflation rates. As a first approximation it could also be assumed that all rates are the same at 14%. In that case equation (33) reduces to

$$n = \frac{P(1+i)}{(S-A)} \qquad (34)$$

$$= \frac{471\,500\,(1+0.14)}{(587\,250 - 131\,200)}$$

$$n = 0.91 \text{ years (11 months)}$$

The previous calculations assume that the concentrated whey is given away free of charge. Revenues generated from the sale of concentrated whey will of course reduce the payback period by a considerable extent.

8 SUMMARY OF OBSERVATIONS

From the data collected over the 592-day technological assessment of the hyperfiltration system for sweet whey, the following observations are made:

1) To produce 1 kg of cheese an average of 9.22 kg of milk are required.
2) For each kg of cheese produced an average of 8.36 kg of raw whey are generated.
3) The mean raw whey solids concentration is 6.24%.
4) La Fromagerie d'Oka processes an average of 39 200 kg of milk per day resulting in an average daily cheese production of 4 256 kg and whey generation of 35 700 kg per day.
5) Ninety-one percent of milk processed ends up as sweet whey.
6) Over the 250-day working period in a year, La Fromagerie d'Oka generates 8.9×10^6 kg sweet whey (@ 6.24% solids).
7) This cheese manufacture plant ranks in the category of small cheese producing plants in Canada. Ninety out of a total of 182 plants fall into this category.
8) Of the 800×10^6 kg sweet whey produced annually in Canada, 48% is processed, 44% wasted and 8% used for animal feed.
9) Sweet whey at an initial solids concentration of 6.24% was concentrated to 24.1% solids using hyperfiltration.
10) Hyperfiltration will recover whey proteins and minerals. The protein and mineral losses in the permeate (1 500 mg/L total solids) were 0.25% and 0.03%, respectively.
11) Important average raw whey characteristics were as follows:

COD	=	64 000 mg/L
BOD_5	=	29 500 mg/L
TS	=	62 400 mg/L
Minerals	=	0.38%
Protein	=	0.9%
Fat	=	0.07%
pH	=	6.22

12) Based on a whey volume of 35.7 m^3/d, these concentrations correspond to 2 280 kg COD, 1 050 kg BOD_5 and 2 230 kg TS per day.
13) A COD/BOD_5 ratio of 2.22 indicates a high degree of biodegradability.
14) The permeate and process washwater (combined effluent) volume was 39.8 m^3/d,

and was characterized by average concentrations as follows:

COD	=	1 700 mg/L
BOD_5	=	880 mg/L
TS	=	4 370 mg/L

15) The total plant effluent has a population equivalent of 450, requires treatment, and nutrients would have to be added.

16) If whey recovery were not practiced then the corresponding community size for joint treatment would be in the order of 3 300 persons, with average daily mass discharges of 2 350 kg COD, 1 090 kg BOD_5 and 2 400 kg TS.

17) The mean daily system flux for the whey permeate was calculated to be 12.1 $L/m^2 \cdot h$. This meets the manufacturer's claim of 12 $L/m^2 \cdot h$.

18) This study demonstrated the impact of product recovery on pollution control. COD, BOD and TS reductions were greater than 95%.

19) From the results of this study a mean solids concentration factor of 3.9 was determined. This compares most favorably with the target factor of 4.

20) If the target solids concentration were 24%, then the optimum process condition would be a hyperfiltration system pressure of 3700 kPa for 11.2 hours using feed of a 6% total solids.

21) For this system configuration the maximum attainable solids concentration appears to be 25.4%.

22) With system operation at 4200 kPa too much time would be needed to reach maximum solids concentration, which would be less than 20%.

23) One hour of operator's time can be saved by operating the system at 3700 kPa to attain 24% solids concentration (as opposed to other pressures).

24) The rate of solids concentration increase is a direct function of the system pressure. The higher the pressure, the greater the rate.

25) The time when a lower rate of solids concentration increase occurred was also a function of pressure. The higher the pressure, the earlier the time.

26) Prediction equations correlating solids concentration as a function of time or conversely the time required to attain a specified solids concentration were developed for different system pressures.

27) A unified equation relating the product of system pressure and time to solids concentration was developed as:

$$C = 6.2\, e^{36.9 \times 10^{-6} Pt} \qquad (18)$$
$$0 \leq Pt \leq 400$$

The 95% confidence interval is $\pm$ 3% solids.

28) A concientious cleaning schedule and procedure for the hyperfiltration system after each run will keep membrane flux losses to less than 10% between the first and fifth day of operation.

29) The instantaneous membrane flux decreases linearily as the whey solids concentration increases.

30) Mathematical relationships for the solids range shown describe these relationships as follows:

$$F_{30} = 28.6 - 1.34\ (\%\ \text{solids}) \qquad (19)$$
$$5 \leq \%\ \text{solids} \leq 21.3$$

$$F_{37} = 29.5 - 1.32\ (\%\ \text{solids}) \qquad (20)$$
$$5 \leq \%\ \text{solids} \leq 22.5$$

$$F_{42} = 34.0 - 1.67\ (\%\ \text{solids}) \qquad (21)$$
$$5 \leq \%\ \text{solids} \leq 20.0$$

31) All instantaneous membrane flux data could be correlated to percent solids with pressure and solids limitation ranges as shown:

$$F = 30.1 - 1.41\ (\%\ \text{solids}) \qquad (22)$$
$$3000 \leq P < 4200\ \text{kPa}$$
$$5 \leq \%\ \text{solids} \leq 22.3$$

32) Using the above equation the maximum attainable solids concentration is 21.3 $\pm$ 1.5% (S.E.).

33) From every 1 kg milk 0.62 kg of permeate result when hyperfiltration is practiced within the process conditions noted in this study.

34) On a mass basis the permeate to concentrate ratio was calculated to be 2.3.

35) Membrane rejection of COD, BOD_5 and TS was observed to be 98.7%, 98.5% and 97.6%, respectively.

36) The percent minerals in the whey permeate increase with increasing solids concentration but is independent of system pressure over the range $3000 \leq P \leq 4200$ kPa. The minerals are associated with the solids phase.

37) The protein concentration in the permeate is independent of solids concentration and system pressure. Protein leakage was constant and resulted in a constant concentration of 0.3%. Proteins, because of their high molecular weight were retained in the concentrate.

38) The mineral concentration in the concentrate could be described by the function:

$$\% \text{ Minerals} = 0.075 (\% \text{ solids}) - 0.051 \quad (24)$$

39) Lower system pressures (i.e., 3000 and 3700 kPa) resulted in lower protein retention in the concentrate as compared to 4200 kPa pressure.

$$\% \text{ Protein} = 0.122 (\% \text{ solids}) + 0.170 \quad (26)$$

40) A correlation between fat and solids in the concentrate was established as:

$$\% \text{ Fat} = 0.012 (\% \text{ solids}) + 0.005 \quad (27)$$

41) Based on these data a sweet whey concentrate with 24% solids will have the following characteristics:

minerals	=	1.75%
protein	=	3.1%
fat	=	0.29%

On a dry basis this translates to 7.3% minerals, 12.9% protein and 1.21% fat, and corresponds to values cited in the literature.

42) During the first 10 hours of any operational day water consumption averaged 1 135 L/h irrespective of the hyperfiltration system operating pressure. Over the next 14 hours water consumption dropped to an average of 300 L/h. The daily water usage has been estimated at 15.5 m^3.

43) Water usage for this cheese producer is calculated to be 0.43 L water per L of whey. Since the water usage target for this industry is 1 L water per L of whey, this is extremely low and indicative of good in-house water conservation practices.

44) The raw water usage to milk processed ratio for La Fromagerie d'Oka is 0.40. This means that 2 L of water are required for every 5 L of milk processed.

45) The 1979 annual cost of producing 24% solids sweet whey from 6% raw whey using hyperfiltration technology was $184 800. This cost, when based on 250 operating days and 2 175 kg solids recovered per day, translates to a daily cost of $739 or 34 cents per kilogram solids recovered.

46) Based on 1983 dollars this cost is adjusted to 46 cents per kg of solids recovered.

47) The distribution of annual costs between maintenance, operation and capital is 19%, 36% and 45%, respectively.

ACKNOWLEDGEMENTS

Responsibility for day-to-day operation, maintenance of the equipment, sample collection, analyses, monitoring and overall management of the project was assigned to Mr. Paul Niedermayr, General Manager, and Jack Duckworth, Operations Superintendent, at La Fromagerie d'Oka.

The scientific liaison officer for the project was Mr. Wayne Bissett from the Water Pollution Control Directorate of the Environmental Protection Service. He was responsible for ensuring the continuity of the project according to the terms of reference and providing scientific and technical advice to the company.

Shortly after the demonstration phase at the project was completed, La Fromagerie d'Oka was sold to Agropur Limited, and the two principals left the company. The consulting firm of N.W. Schmidtke and Associates Ltd. was then engaged to complete the data analysis and prepare the technical project report.

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